Improved Polyurethane Storage Tank Performance

Contract No. SP0600-04-D-5442, Delivery Order 1029

FY2009 Final Technical Report

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14. ABSTRACT

The Improved Polyurethane Storage Tank Performance program was sponsored by Defense Logistics Agency Energy (DLA Energy) to study polyurethane coated membrane fabrication processes that are or may be used in the production of collapsible fuel tanks (CFT). The objective of this effort was to provide technical information that will assist in the improvement of polyurethane storage tank performance through the development of improved tank construction, fabrication techniques and quality control procedures. This research program expands on the FY2008 published effort by integrating in CFT fabrication and quality control recommendations and evaluating tank leaks through laboratory and actual field study.

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Table of Contents   Page

<u>Appendices</u>

Acronyms

ALC – Air Logistics Center
AO – alternate overlap weld
APC – Army Petroleum Center
ARL – Army Research Laboratory
BRAG – leak visual rating system
CFD – computational fluid dynamics
CFT – collapsible fuel tank
DBS – double butt seam
DLA – Defense Logistics Agency Energy
DLC – dead load chamber
F/B – face/back – referring to face and back side polyurethane coatings
FEA – finite element analysis
FMEA – failure mode effects analysis
FOPW – fold over prayer weld
FTA – fault tree analysis
HAW – hot air welding
HTF – high temperature fuel
LTR – leak test rig
RF – radio frequency welding
RPN – risk probability number
SME – subject matter expert
SO – shingle overlap weld
SwRI – Southwest Research Institute
TARDEC – Tank Automotive Research, Development and Engineering Center
TPU – thermoplastic polyurethane
TTSSP – time-temperature-stress superposition method

Units

lbs_f/in – pounds force per inch
psf – pounds per square foot
psi – pounds per square inch
°F – degrees Fahrenheit
°C – degrees Celsius

1.0   Executive Summary

1.1   Material Equivalency Statement

The material selected for the Improved Polyurethane Storage Tank Performance study (Contract No. SP0600-04-D-5442) was Seaman Corporation's 1940 PTFF MS337. This fabric is currently in use in U.S. Air Force and Army collapsible fuel tank contracts. It was the test material for the original FY2008 CFT research project focusing on the structural integrity of tank seams (Delivery Order 1017). It was also selected for use as the material for this study, the FY2009 CFT program (Delivery Order 1029). A list of the specific lot and material rolls used is located in Section 4.5.1.

1.2   Program Summary

The Improved Polyurethane Storage Tank Performance program was sponsored by Defense Logistics Agency Energy (DLA Energy) as a congressionally mandated research project to study polyurethane coated membrane fabrication processes that are or may be used in the production of collapsible fuel tanks (CFT). The objective of this effort was to provide technical information that will assist in the improvement of polyurethane storage tank performance through the development of improved tank construction, fabrication techniques and quality control procedures. The FY2009 research program expands on the FY2008 published effort (Improved Polyurethane Storage Tank Performance, FY2008 Final Report), by integrating in CFT fabrication and quality control recommendations and evaluating tank leaks through laboratory and actual field study with JP-8 fuel.

Seaman Corporation successfully completed the FY2008 CFT research project focusing on the structural integrity of tank seaming methods. This contract ran through December 31, 2010. A design of experiments was utilized to study fuel tank seam integrity through various seam fabrication technologies with deadload testing in fuel as identified in MIL-PRF-32233 as the foundation. The fabrication processes evaluated during this project included thermal impulse, radio frequency, hot bar, hot air and hot wedge. Welded samples representing each fabrication technique were placed in a deadload chamber in heated fuel for a total of 62 days. During a 62-day period, each fabrication technique was subjected to increasing load and increasing temperature. After Day 62, the samples were removed from the chamber and analyzed to determine the mode of seam failure. The robustness of the studied seam fabrication techniques under deadload in fuel conditions was instrumental in determining the foundation of the FY2009 program phase.

During the course of this program, Seaman Corporation evaluated fabrication techniques, overall tank designs and quality control procedures in the areas of general seams, end closures, corners and fittings with an emphasis on preventing fuel leaks. Early in the effort, the decision was made to tap into the extensive field experience and the records of Collapsible Fuel Tank end users to help define the scope of the program. Seaman Corporation coordinated a technical roundtable session which included designated representatives from industry and the military. Information gathered in the roundtable session along with field reports were used to identify the root cause of CFT leaks and to brainstorm ideas for potential solutions.

1.3   Collapsible Fuel Tank Design and Qualification Recommendations

A number of important conclusions were reached during the course of the program. These will be discussed in depth in the following sections. They are broken down by area of impact: tank failure analysis, tank design and fabrication, tank qualification testing, laboratory and field performance. The scope of the test program was clearly defined in the Technical Proposal dated 21 JUN 11, reviewed and approved by DLA. The results contained within this document cover what deliverables were defined in

the Technical Proposal as well as any additional discoveries made beyond the scope of the original proposal.

Relative to tank geometry, any design which minimizes welded seams, especially T-welds, closing seams and corners, should help reduce the probability of leak occurrence. In addition, for seams joining warp panels and closing seams, double-butt welds provided the most consistent performance. Corners that required the welding of more than 2-plies of material to seal proved problematic. Reinforcement of these corners with through-hole bolts clamps only created an additional leak path.

Upon filling, any design where the base of the tank is allowed to lift off the ground (e.g., the corners of a standard design tank (pillow tank)) will impart additional stress in the tank material. This was offset in this study in the prototype designs through two methods, 1) designs which keep the base grounded, and 2) which included additional material (5-15%) to allow for proper center and side expansion without edge lift.

Lastly, the current use of strapping charts may be leading to tank failures by not allowing for field temperature correction and overfilling based on field tank stretch. The strapping chart created by a fabricator with cold tap water gives a height versus volume relationship based on lower temperatures. Once the tank is deployed, typically in maximum temperatures which may exceed 110 – 120 °F, a target height established at the factory may cause the tank to be filled in excess of the 110% volume specification.

A concise summary of study findings is located in Section 7.1.

2.0   Introduction

2.1   Problem Statement

The Defense Logistics Agency Energy (DLA Energy) enlisted Seaman Corporation to manage a congressionally-mandated research project to study polyurethane coated membrane fabrication processes that are or may be used, in the production of collapsible fuel tanks (CFT). Seaman Corporation is a United States company currently engaged in the development and production of polymer coated fabric systems for industrial and military applications. The objective was to provide technical information that will assist in the improvement of polyurethane storage tank performance through the development of improved tank construction, fabrication techniques and quality control procedures. The focus of the FY2009 research will build on the FY2008 published effort (Improved Polyurethane Storage Tank Performance, FY2008 Final Report), evaluating tank leaks.

2.2   Project Milestones

Per the Technical Proposal, the following major milestones were established and met through the course of this program:

MILESTONE		COMPLETED
Technical Round Table		February 2010
Test Site Selection		April 2011
Tank Farm Design / Layout		June 2011
Model Tank Design, Fabrication and Testing		June 2011
Fabricate Final Design Tanks with Acceptable Fabrication Methods – verify scale up with water		April 2012
Test Final Design Tanks – Long Term Cycle Testing		December 2013
Parallel Testing in Deadload Chamber and with Leak Test Rig		December 2013
Technical Report		June 2014

2.2.1   Failure Analysis Summary

Fault Tree Analysis (FTA) and Failure Modes Effects Analysis (FMEA) were undertaken to help identify the contributing factors and root cause of failures for CFT designs. This method was used to help define experimental inputs for both the laboratory and field tank testing. A detailed description of the results of these analyses is located in Sections 3.2 and 3.3.

2.2.2   Tank Design Summary

A series of scale model tanks were fabricated and filled with water at Seaman Corporation to evaluate various aspects of tank design. These designs were based on previous lessons learned and served as a method for pairing down multiple design ideas into a manageable number for the long-term field testing at the Southwest Research Institute (SwRI) in San Antonio, TX. Tank design considerations such as tank shape and geometry, panel orientation, closing seams and joining seams were evaluated against overall tank performance as a function of fill volume and environmental conditions.

A number of current, qualified fabricators were contacted and interest was gauged. Seaman Corporation reviewed the field tank designs with the two participating companies to get their input regarding potential fabrication methods, techniques and any potential recommended design changes.

2.2.3   Field Testing

The Tank Farm Field Testing was conducted at the Southwest Research Institute (SwRI) in San Antonio, TX. Seaman Corporation provided fabricated, qualified tanks, as well as direction and oversight to the operation of the Tank Farm. The Tank Farm went online in mid JUN 12 and ran through the middle of DEC 2013 (i.e., 18 months). SwRI provided the day-to-day supervision, operation and data collection for the test. The data collected included: 1) BRAG observation of tank defects in accordance with TB 10-5430-253-13 - TECHNICAL BULLETIN FOR COLLAPSIBLE FABRIC FUEL TANKS, 2) warp and fill stretch measurements, 3) tank skin temperature, 4) tank height, volume and footprints, 5) daily local climatic conditions, and 6) JP-8 fuel handling and quality associated measurements. The JP-8 fuel met the MIL-DTL-83133 requirements with the possible exception of the maximum -47°C freeze point.

This exception was accepted and approved by DLA in the original Technical Proposal. The Tank Farm Field Testing was completely defined and specific responsibilities and liabilities detailed in the Seaman Corporation Services Agreement and associated SwRI Statement of Work.

Seaman Corporation procured from existing, qualified CFT manufacturers twenty 3K fuel tanks and a single 50K tank. The 50K tank served as a reserve back-up tank, fuel distribution source and as an initial verification for stretch measurements for the 3K tanks.

To verify tank integrity prior to shipping to SwRI for fuel based testing, all tanks (both 3K and 50K) were air and water tested at the tank fabricators' facilities per MIL-PRF-32233. For each design tested at SwRI, there was at least one standby tank if needed. The need to use the standby occurred with only one tank, the original Tank 16, which was replaced with Tank 17-2.

The JP-8 fuel was brought to the Tank Farm in a 3,000 gallon SwRI tanker with a pump and meter on board. The 50K safety reserve tank was first filled to 50,000 gallons prior to shuttling fuel off to the 3K test tanks. Once the 50K was filled, it was allowed to settle and equilibrate with the climate for approximately one week. Stretch measurements were then made to verify the warp and fill stretch baseline thresholds for the 3K overfill studies.

At the SwRI test site, the 20, 3K-gallon CFTs were connected by hoses in pairs to allow for cycling of fuel back and forth once a week. Initially, all the tanks were filled to 3,000 gallons so that a 100% fill baseline could be established. The tanks were allowed to settle and come to equilibrium with the climate before baseline measurements were taken. Next, tank overfill shuttling was initiated. One tank in each pair overfilled to 130 – 150% of the design volume (3,000 gallons).

This was done to simulate stress encountered in larger (e.g., 50K to 210K) tanks, as was determined in the FY2008 effort and verified with the 50K. Once overfilled, the tanks were allowed to sit and equilibrate to the local climatic conditions for one day. Stretch measurements were made on two panels per tank daily for four days. The process was then repeated by transferring the fuel from the overfilled tank to the under filled tank. Throughout the 18 months of testing, SwRI inspected the fuel farm five days a week and made the following measurements and observations:

- Determined if any tanks were exhibiting wetting or degradation and observed and recorded, per the TB 10-5430-253-13 BRAG evaluation criteria, panel, seam, blister/separation, seam separation and fitting performance for each tank.

- Panel stretch measurement on each tank. Grids were drawn and measured in both the warp (X) and fill (Y) directions with a caliper. A daily total of 20 grid measurements were made.

- Recorded whole tank thermal image with an IR camera on the side of the tank most directly exposed to the sun.

- Tank volume was verified through tank height with plumb lines and the use of flow meters during filling.

- Daily ambient weather and temperature conditions were tracked and recorded to gauge the impact of environment on tank performance.

At the end of the test period, any tank area which exhibited a leak of interest was extracted and returned to Seaman Corporation for forensic evaluation to help gauge tank performance and/or determine potential cause of failure.

Tank performance updates were provided by Seaman Corporation on a quarterly basis and are located in the Appendices W thru BB.

2.2.4   Laboratory Testing

Seaman Corporation designed and developed a test apparatus, the Leak Test Rig (LTR) for evaluating leaks in CFT design features. The LTR allows for controlled exposure of material, seam and tank sections to high temperature, pressurized dyed water over extended time periods. These leaks were either induced in material (e.g., abrading the coating on the inside /outside) or extracted from tank sections of interest.

Dead load testing was also conducted on seam samples not previously tested in the FY2008 effort. This included a variety of end closure seams and differing closure seam geometries. The samples were exposed to JP-8 under load and temperature conditions defined by the Time-Temperature-Stress Superposition (TTSSP) method successfully used in FY2008. This allowed for a 29-day acceleration which would equate to three years exposure. The seams tested reflected, where applicable, the welds employed in the FY2009 Tank Farm 3K CFTs as well as investigational weld designs from the model tank evaluations.

3.0   Failure Analysis

3.1   Department of Defense Collapsible Fuel Tank Acquisition Roundtable

A CFT Technical Roundtable Meeting was held on December 10, 2009 at the Residence Inn in Woodbridge, VA. The purpose of this Seaman Corporation-sponsored roundtable was to discuss testing ideas with attendees with a variety of CFT experience. Attendees included individuals who were military fuel handlers, CFT engineers and manufacturers. Government agencies represented at the roundtable included DLA (previously DESC), TARDEC, ALC, ARL and APC. Military branches included US Army, USMC and the USAF. Industry attendance included Applied Geo Technologies, Berg Integrated Systems, MPC Containment, GTA Containers and Seaman Corporation.

This meeting was followed up by CFT Acquisition Roundtable Meeting conducted May 12, 2010 at the Gaylord National Hotel and Convention Center, National Harbor, MD. The purpose of this May meeting was to provide a forum to discuss issues as well as solicit ideas on CFT acquisition from the perspective of both the Governmental Agencies (i.e., Department of Defense – DoD) and Commercial Industry.

The meeting was limited to half a day, so sessions were optimized to make the most of the time available. The process consisted of four steps:

1)   Exploring and capturing issues,
2)   Identifying possible countermeasures,
3)   Assessing the feasibility of the proposed solutions, and
4)   Evaluating the impact of the solutions.

At the conclusion, representatives from the industry and government focus groups briefed all attendees on the issues across three identified areas: Acquisition, Quality Standards and Performance Failures.

The following lists these general areas identified for potential improvement:

- Improving teaming between industry and government in areas of long-term planning, determining delivery order requirements and projecting funding for contract execution.

- Revising the acquisition process to potentially include economic price adjustment provisions to account for changing market conditions. Also, revising delivery order practices and increasing opportunities for competition.

- Improving feedback on CFT performance through critical data identification, gathering, and analysis.

- Reviewing optimum lot size and conformance testing requirements to realize both logistical and quality benefits.

- Developing proven field repair procedures including material-specific repair kits and instructions.

Detailed reports of the roundtable discussions can be found in Appendix A.

Based on roundtable representative field experiences, an estimate of the different contributing CFT issues was created. Figure 3.1.1 is a Pareto which captures the estimated frequency of occurrence for the most common defects. Eighty percent of the failures are seam related closing seams, panel seams and corners (a type of seam) being the contributing sources. Material compound blisters, fitting related leaks and all others factors make up the remaining 20% sources of failures.

Figure 3.1.1 – Pareto of Roundtable Polyurethane Tank Concerns
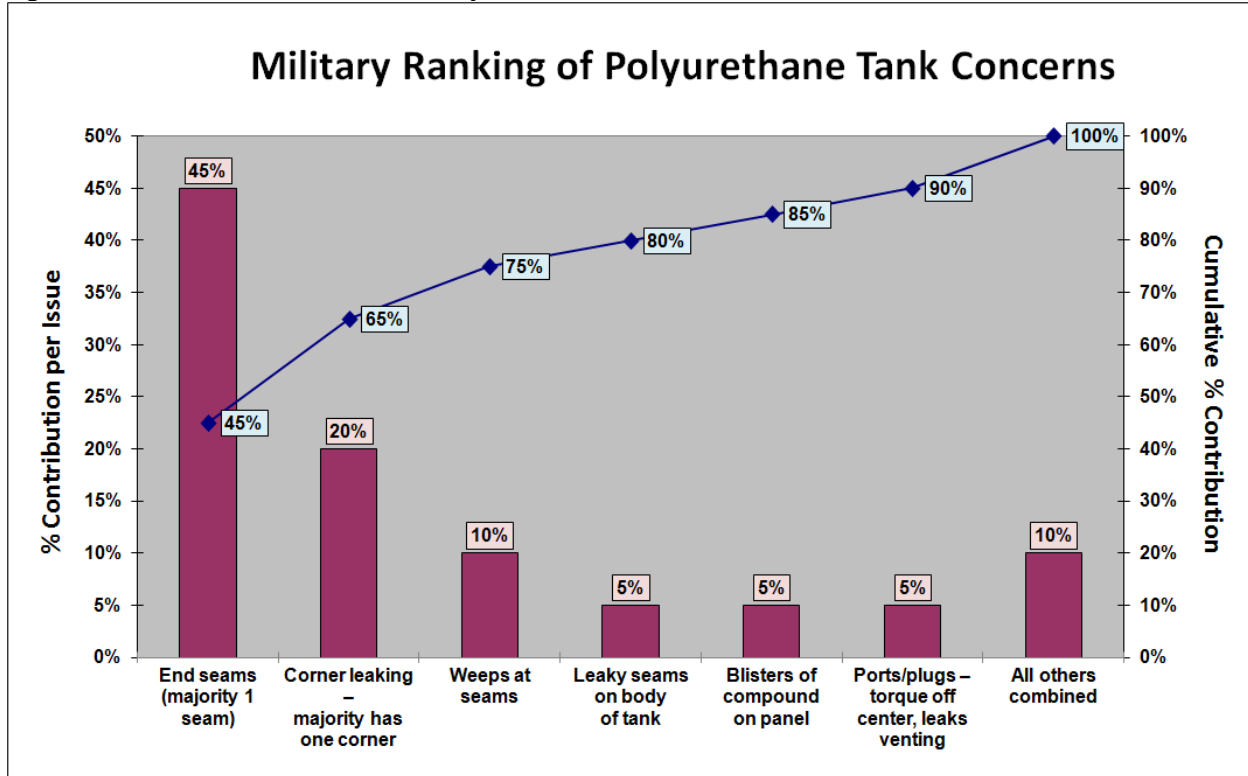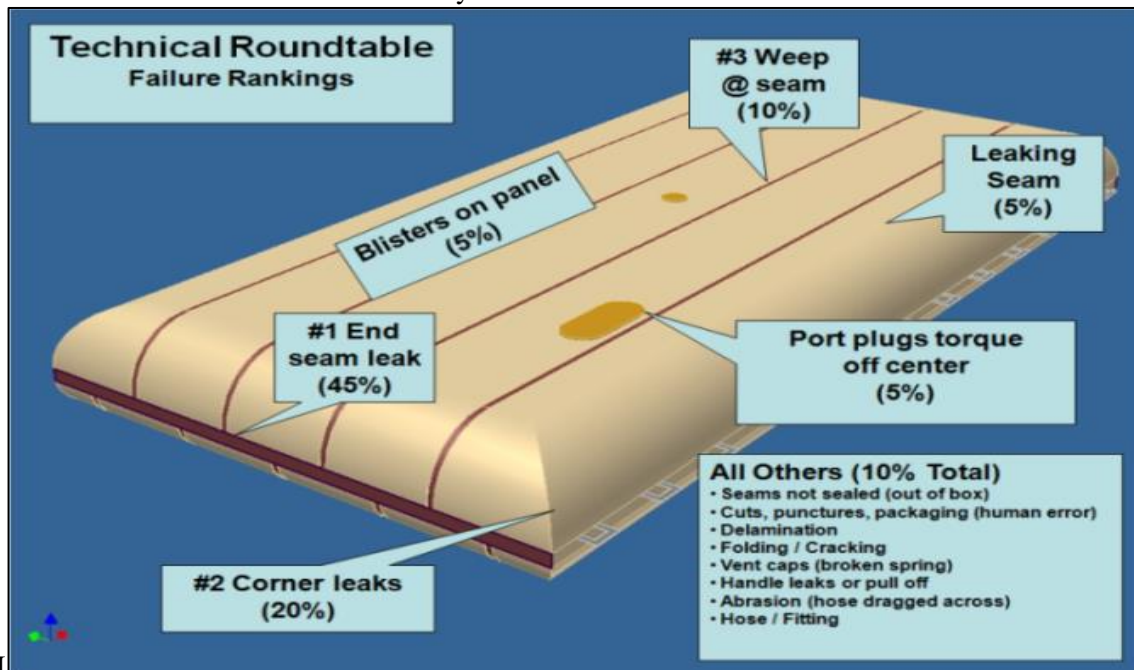

Figure 3.1.2 further classifies the data captured in the Pareto chart and identifies contributing factors relative to their typical location on the CFT. In addition, it lists the remaining items (all individually less than 2%) which make up the "All Others" category.

Figure 3.1.2 – Schematic of Roundtable Polyurethane Tank Concerns

These issues were discussed at length at the beginning of the Failure Analysis working sessions and served as the foundation for much of the inputs into the Fault Tree and Failure Modes Effects Analysis.

3.2   Fault Tree Analysis

The creation of a collapsible fuel tank is an effort that involves multiple organizations and systems operating together successfully (e.g., material manufacturer, tank fabricator, field operations). To understand where failures in these systems occur, a top down, deductive, convergent failure method, Fault Tree Analysis (FTA), was undertaken. This is an encompassing analysis which attempts to capture every possible root-cause that could contribute to an overall failure. In practice, many of the root-causes that emerge are rare occurrences. Used commonly in reliability and safety engineering, FTA allows for identification of root causes by starting with the top level "worst case" system failure. After these undesired states have all been defined, deductive Boolean logic (i.e., "and" / "or") is utilized to determine all of the possible causes which may contribute to or create the top level failure. An "or" gate situation is one where any one of the underlying events may occur and cause the top level failure. For an "and" gate, all of the underlying events must occur simultaneously.

For the purposes of this effort and based on previous team discussion and agreement, some CFT pertinent definitions were created for use relative to the root cause analysis effort. Leak paths were defined:

- Multiple Leak Path - an "and" fault that requires both an internal source and an external path
- Internal Leak Sources – allows fluid into the fabric
- External Leak Paths – path which shows leak on exterior of tank
- Single Leak Path – as name suggests, a through pathway or "or" fault

In addition, six CFT specific leak types were evaluated:

Collapsible Fuel Tank System Legend	
1.0	Panel Leak
2.0	Weld Leak
3.0	Closing Seam Leak
4.0	Corner Leak
5.0	Fitting Leak
6.0	Handle Leak

A *panel leak* refers to any flaw in the body of the panel not associated with the seams. A *weld leak* refers to the panel seam welds that run along the long warp axis of the panel. A *closing seam* leak refers to the end closures that are typically used to "close" the open ends of the tank. *Corner leaks*, as the name suggests, refer to four corners of the tank. *Fitting leaks* refer to manway / filler / discharge, vent and/or drain assemblies. *Handle leaks* refer to the handles attached to certain tank designs for ease of deployment.

An example of an FTA analysis for leak type (2.0) Weld Leak is included in Figure 3.2.1. The full FTA analysis can be found in Appendix B. The top level event for this example is a 2.0 Weld Leak. From here, there are only two "or" options available: a 2.1 Multiple Path Leak "or" a 2.2 Single Path Leak. The Multiple Path Leak has two required "and" legs that must happen for a leak to occur. For example, a leak may form if event 2.1.1.1.2.5 Tape Embrittlement occurs on an interior weld inside the tank "and" event 2.1.2.2.4 Improper Use of Solvent occurs on the exterior on the same panel. This will be true for any combination of a single Internal "and" a single External Leak source. By comparison, only one event

must occur under the Single Leak Path for a leak to appear in a weld. By systematically reviewing each of the six defined possible CFT leak types, a comprehensive list of all probable root causes was created

Figure 3.2.1 – Fault Tree Analysis (FTA) Weld Leak Example
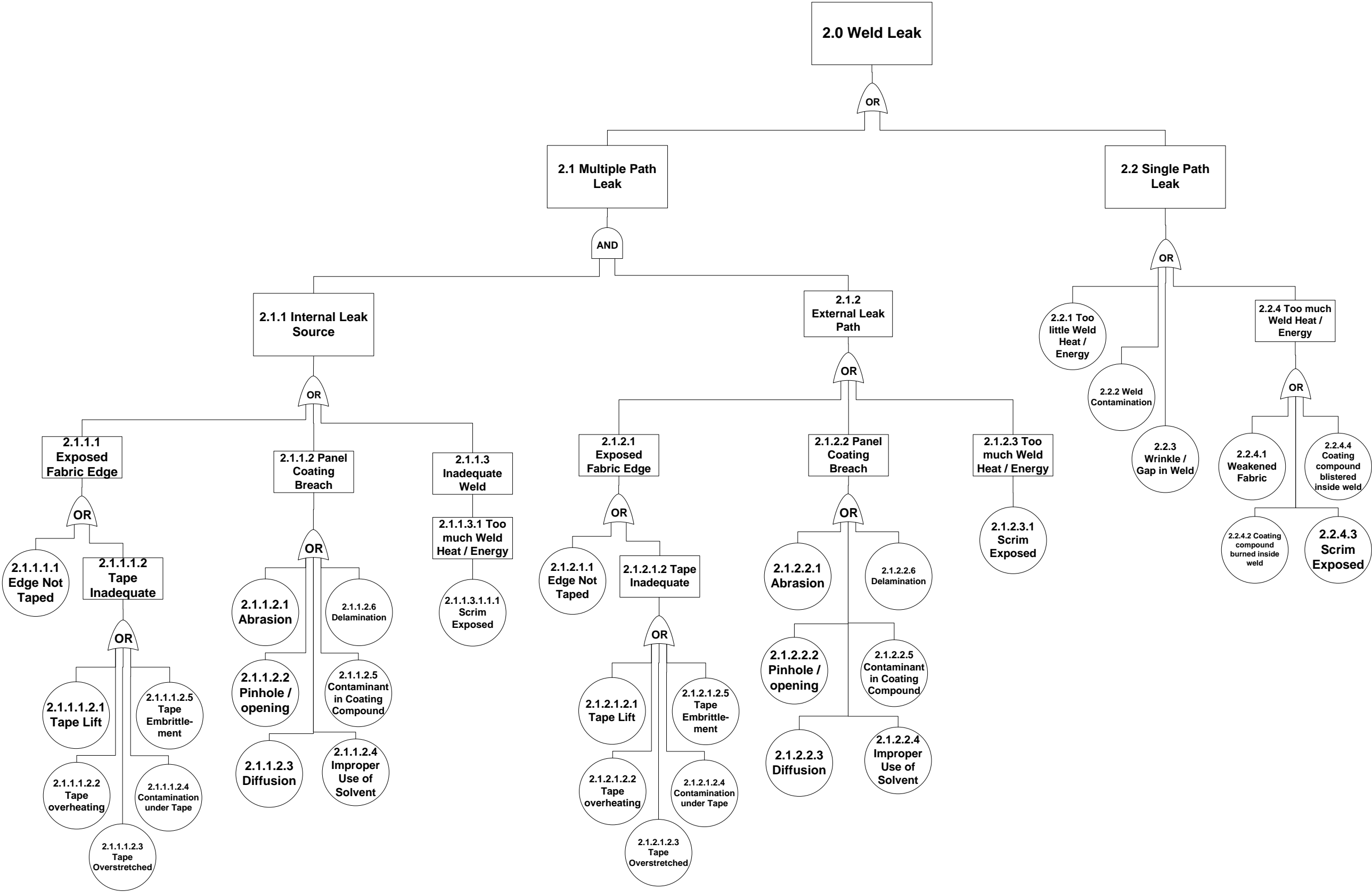
3.3   Failure Modes Effects Analysis (FMEA)

Once the underlying causes of the top level failure are determined, it is possible to create a remediation and control plan through a divergent, inductive method known as Failure Mode Effects Analysis (FMEA). Unlike the FTA, an FMEA is a bottom-up approach which starts with the underlying components and root causes that create the catastrophic top-level failure. The FTA, if it is comprehensive, can be used to create the list of all probable root causes for use in the FMEA. This is the method employed in evaluating the Collapsible Fuel Tanks (CFTs), considering their Design, Process and Functionality. Once the Failure Modes have all been defined, a careful Analysis of all of the potential Effects results in a Risk Priority Number (RPN). As the name suggests, this value is used to help qualify and prioritize the level of attention each root cause should require for appropriate remediation. The RPN is calculated by multiplying weighted values for the root causes Severity, Occurrence and Detection (i.e., RPN = S x O x D). *Severity* is defined from minor (e.g., no noticeable impact on performance - value = 1) to very high (e.g., impacts safety or government compliance – value = 9-10). *Occurrence* is defined as the probability of happening from unlikely (1) to inevitable (9-10). *Detection* is the ability for the event or root cause to be detected before failure. For a CFT, a Detection of 1 indicates that the problem can be readily detected prior to use (i.e., filling the CFT with fuel). A Detection value of 10 would suggest that there is no known means of finding the problem prior to use of the CFT. The definitions for all the Severity, Occurrence and Detection rankings are located in Tables 3.3.1 through 3.3.3. CFT is fabricated from a flexible material that makes it ideal for deployment and easy installation. Therefore, due to this nature, CFT scores higher in certain weighted values. Typically, there is no available real-time method of detection (e.g., material flaw, over cooked weld, etc.) with a CFT as there might be with an electro-mechanical system. Occurrence values may also trend higher since the probability increases with the number of processes the tank is exposed to during fabrication (e.g., hand held heat gun flaw on inside of tank while installing a patch).

Table 3.3.1 – Severity Ranking Definition for FMEA

Severity

Effect	Rank	Criteria
Minor	1	No noticeable effect. User will not detect failure.
Low	2-3	Slight user annoyance. Slight CFT deterioration or performance reduction.
Moderate	4-5-6	User dissatisfaction / ongoing repair. CFT performance deterioration. Unscheduled repairs (not Recommended Preventative Maintenance).
High	7-8	User highly dissatisfied. Inability to continue CFT use. Out of service.
Very High	9-10	Safety or non-compliance with requirements. Potential danger to user or site.

Table 3.3.2 – Occurrence Ranking Definition for FMEA

Occurrence

Effect	Rank	Criteria
Remote	1	Failure unlikely. No failures ever associated with CFT or similar tanks.
Very Low	2	Only isolated failures associated with this CFT or similar tanks.
Low	3	Isolated failures associated with similar CFTs.
Moderate	4-5-6	Occasional failures with this CFT or similar tanks.
High	7-8	CFT or similar tanks fail often.
Very High	9-10	Inevitable CFT failure. 9 for failure with some warning. 10 for failure without warning.

Table 3.3.3 – Detection Ranking Definition for FMEA

Detection

Effect	Rank	Criteria
Very High	1	Failure always detected during fabricator inspection or qualification. Failure detected prior to install.
High	2-3	Failure good chance of detection during fabricator inspection or qualification. Good chance of failure detection prior to install.
Moderate	4-5	Failure not detected by fabricator but detected by user when inspected upon receipt. May detect prior to install, absolutely before use.
Low	6-7	Failure may be detected by user when received or during installation. Failure absolutely detected during first use.
Very Low	8-9	Failure poor chance of detection by user when received or during installation. Failure probably not detected during first use.
Undetectable	10	Failure not detectable prior to use. No known direct method of detection.

An excerpt from the CFT FMEA is shown in Table 3.3.4. Each root cause defined in the FTA is listed in the second column (e.g., "Too much Weld Heat – Energy"). The potential failure mode associated with the specific root cause is listed in the first column. For example, for the root-cause stated above, a Multiple Path / Internal Leak Source / Exposed Fabric Edge / Inadequate Weld covers the potential path for the leak. The Effect Description details the impact of the root-cause for this instance. The values of Severity / Occurrence / Detection were then assigned for 8, 5 and 9 respectively. From this, an RPN of 360 was calculated (8x5x9 = 360). A threshold RPN of 120 was established by the team as a minimal cut-off for further evaluation.

A copy of all of the FMEA evaluation tables is located in Appendix C.

Table 3.3.4 – Example from FMEA Tables

Potential Failure Mode	Cause(s) of Failure	Effect Description	Severity	Occurrence	Detection	RPN
Multiple Path Leak						
Internal Leak Source						
Exposed Fabric Edge						
Tape Inadequate	Tape Lift	Fuel ingress into coated fabric	6	5	8	240
	Tape Overheating		4	4	9	144
	Tape Overstretched		4	4	9	144
	Contamination Under Tape		6	4	5	120
	Tape Embrittlement		4	5	10	200
Inadequate Weld	Too much Weld Heat / Energy - Scrim Exposure	Fuel ingress into coated fabric	8	5	9	360
	Too little Weld Energy		8	5	8	320
	Weld Contamination		8	3	9	216
	Wrinkle / Gap in Weld		8	3	9	216

In addition to defining and controlling negative impacts, the combination of FTA and FMEA can be used as inputs for designing heartier, more robust systems. This information was reviewed along with the field and Technical Roundtable reports and used for field prototype tank and experimental design. In the approved program technical proposal, three methods of empirical testing were committed to, including the Tank Farm testing at SwRI, the Dead Load seam testing and the Leak Test Rig. Summarizing the outputs from the FMEA, the process of determining the best test method for modeling each root cause was determined. The results of this effort are shown in the Tables 3.3.5 – 3.3.8. For each root cause (Cause of Failure), the Leak Path (S – single or M – multiple), the Source (I – internal, E – external or T – Through), Potential Failure Mode, Cause of Failure and RPN were listed. A primary test method was then recommended for the Tank Farm (T), the Dead Load (D), the Test Rig (R) or None (N). Although recommended, it is possible that the root cause has been covered by more than one method.

Table 3.3.5 – Material-Based Root Causes

					Material	
					Design	T - Tank Farm
					Fabrication	D - Dead Load
					Use	R - Test Rig
Leak Path (S or M)	Source (I, E, T)	Potential Failure Mode	Cause(s) of Failure	RPN	Failure Mode	Test Method
M	I	Panel Coating Breach	Delamination	360	Material	R
M	I	Panel Coating Breach	Pinhole / Opening	175	Material	R
M	E	Panel Coating Breach	Delamination	256	Material	R
M	E	Panel Coating Breach	Pinhole / Opening	140	Material	R
M	E	Blister(s) (T4-5%)	Delamination	192	Material	R

Table 3.3.6 – Design-Based Root Causes

					Material	
					Design	T - Tank Farm
					Fabrication	D - Dead Load
					Use	R - Test Rig
Leak Path (S or M)	Source (I, E, T)	Potential Failure Mode	Cause(s) of Failure	RPN	Failure Mode	Test Method
M	E	Welding Multiple Layers (> 2)	Fold Over Weld (prayer weld?)	200	Design	T, D
M	E	Welding Multiple Layers (> 2)	T-weld	160	Design	T, D
M	E	Welding Multiple Layers (> 2)	Multi-sheet bending (closing like Seaman RF?)	135	Design	T, D
M	E	Inadequate Corner Reinforcement	Compression Set Failure	150	Design	T, D, R
M	E	Improper Tank Fitting Assembly	Compression Set Failure	150	Design	T
M	E	Fabrication Related Material	Scrim Exposed	225	Design	R
M	E	Fabrication Deficiency	Multiple Ply / Single Ply Interface Associated Stress Increase	256	Design	T, D

Table 3.3.7 – Fabrication-Based Root Causes

					Material	
					Design	T - Tank Farm
					Fabrication	D - Dead Load
					Use	R - Test Rig
Leak Path (S or M)	Source (I, E, T)	Potential Failure Mode	Cause(s) of Failure	RPN	Failure Mode	Test Method
M	I	Exposed Fabric Edge	Tape Lift	240	Fabrication	D, R
M	I		Tape Embrittlement	200	Fabrication	D, R
M	I	Exposed Fabric Edge	Tape Overheating	144	Fabrication	D, R
M	I	- Tape Inadequate	Tape Overstretched	144	Fabrication	D, R
M	I		Contamination Under Tape	120	Fabrication	D, R
M	I		Too much Weld Heat / Energy - Scrim Exposure	360	Fabrication	D,R
M	I	Inadequate Weld	Too little Weld Energy	320	Fabrication	D, R
M	I		Weld Contamination	216	Fabrication	D, R
M	I		Wrinkle / Gap in Weld	216	Fabrication	D, R
M	E	Too much Weld Heat / Energy	Scrim Exposed	240	Fabrication	D, R
M	E		Too Little Heat / Energy	168	Fabrication	D, R
M	E		Weld Contamination	162	Fabrication	D, R
			Too Much Heat / Energy			
M	E	Inadequate Weld	Scrim Exposed	216	Fabrication	D, R
M	E		Weakened Fabric	192	Fabrication	D, R
M	E		Coating Compound Burned Inside Weld	150	Fabrication	D, R
M	E		Coating Compound Blistered Inside Weld	135	Fabrication	D, R
M	E	Improper Tank Fitting Assembly	Over- or Under- Torque of Bolts	192	Fabrication	T
M	E	Fabrication Related Material Failure	Bulk Head Fitting O-Ring Damaged	270	Fabrication	T
M	E		Hole Not Located Correctly	162	Fabrication	T
M	E		Hole Not Correct Size (per Drawing)	162	Fabrication	T

Table 3.3.8 – Handling / Use Based Root-Causes

					Material	
					Design	T - Tank Farm
					Fabrication	D - Dead Load
					Use	R - Test Rig
Leak Path (S or M)	Source (I, E, T)	Potential Failure Mode	Cause(s) of Failure	RPN	Failure Mode	Test Method
M	E	Crack or Fold (T5-1%)	Misuse of solvent	288	Use	R
M	E		Improper handling	288	Use	N
M	E		Improper Storage Condition - temperature	200	Use	N
M	E		Improper Storage Condition - fold	160	Use	N
M	E	Abrasion (T5-1%)	Tank Dragged Across Rough Terrain	288	Use	N
M	E		Hose / Fitting Dragged across Tank	192	Use	N
M	E	Panel Coating Breach	Improper Use of Solvent	240	Use	R
M	E		Abrasion	175	Use	R
M	E	Exposed Fabric Edge -Tape Inadequate	Tape Embrittlement	160	Use	R

The three test methods employed were then designed to capture and evaluate the greatest number of high impact root causes summarized in these tables.

4.0 Tank Design and Fabrication

Seaman Corporation's 1940 PTFF MS 337 was selected as the material to be tested throughout this program. The tank Performance Specification, MIL-PRF-32233 covers five tank sizes. For Sizes I – IV (3,000 – 50,000 gallons), 1940 PTFF MS 337 is the recommended material. For Size V, Seaman Corporation's Style 7150 PTFF is the recommended material.

4.1 Tank Material Selection

Seaman's 1940 PTFF MS337 fabric was selected because it can be used with a wide variety of welding methods to successfully produce a collapsible fuel tank, including hot air, hot bar, hot wedge, impulse and radio frequency welding. Due to the nature of its polyurethane coating, it is adaptable to welding methods, forming a structurally integral bond where two material panels effectively are merged to become one. Hence, it does not rely on solvent based gluing for seam adherence and leaks and seam rupture issues associated with such systems.

For the purposes of this program, a single lot of Seaman 1940 PTFF MS337 fabric was dedicated to the fabrication of 3K tanks which were used in the fuel farm, dead load and leak test rig studies. The rolls within the lot were characterized and tested to assure within-lot consistency. A single lot was chosen for the work to minimize the variables in the laboratory studies. The test data verifies compliance to MIL-PRF-32233 for the lot of material used and can be found in Section 4.5.1 Material Lot Selection.

4.2 Design Approach and Considerations

When evaluating multi-variant systems, it is critical to spend the appropriate time, upfront, to make sure all aspects of the problem are captured and evaluated. With CFTs, there are a number of contributing factors to tank performance. These include, but are not limited to: 1) material manufacturing, 2) tank fabrication, and 3) post-fabrication events which included shipping, storage, deployment and daily operation. To thoroughly analyze the variables that would impact CFT performance, a number of proven problem-solving methods were employed. These methods and sources included FTA, FMEA, field reports (QDR) and results from the Technical Roundtable. These problem-solving methods and sources are summarized in Section 3.

In addition to these methods, multiple observations of how a standard design tank performs were captured during the FY2008 Model Tank testing and confirmed in the field studies. To best understand the fundamental mechanics of how a standard design tank functions, one needs to know how it is constructed. The simplest standard design tank panel layout schematic is in Figure 4.2.1). The six panels are welded to each other first, overlapping along the warp (long) direction of the material. After the panels are welded to form a rectangular blanket, the outer edges of the blanket are welded to each other to form a tube. Both ends of the tube are then welded independently to form closing seams to complete the standard design tank (Figures 4.2.2 and 4.2.3).

The welds along the warp seams are typically either shingle or alternate overlap or double butt seam. The details of these welds are are shown in Figures 4.2.4 to 4.2.7. The closing seams are typically a bottom flap over top shear seam, a fold over prayer weld or a double butt seam. Material ring or oval doublers or triplers are added in the panels where the vent, filler-discharge manway and/or drain are located for additional support for the cast fittings and fasteners.

Figure 4.2.1 – Typical Standard Design Tank showing elevated corners and ends
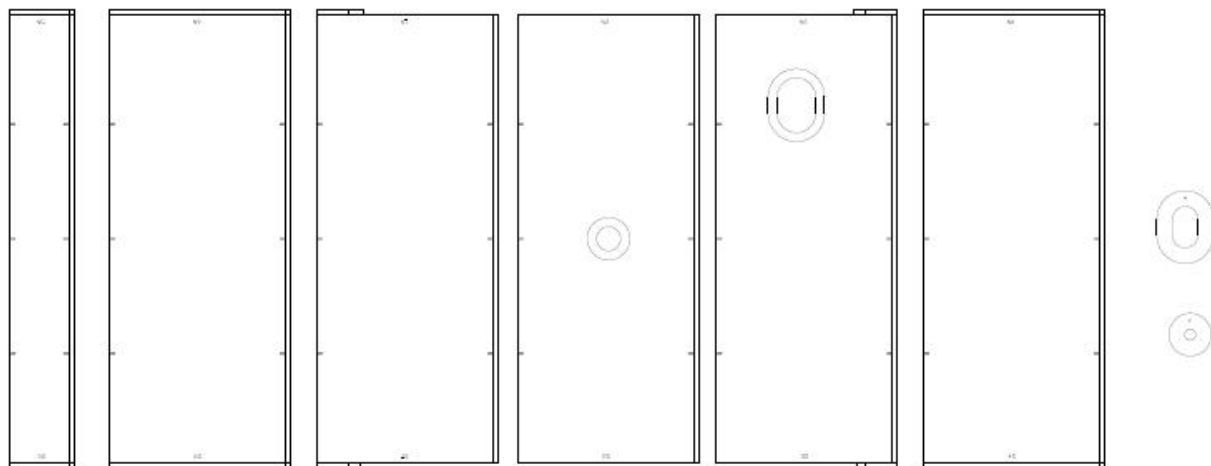
As the tank fills, the center of the tank rises quicker than at the edges due to the way the tank is fabricated and the constraints imposed by its welded geometry. This causes the peripheral edges of the tank to lift into the air, creating the characteristic standard design tank profile. This is clearly evident in the pictures from the test site (Figure 4.4.16).

Figure 4.2.2 – Corner View of Typical Standard Design Tank

Figure 4.2.3 – End View of Typical Standard Design Tank

The FY2008 effort presented extensive findings relative to different welding methods as well as different styles of seams. For warp panel welds, three types of seams are typically employed: shingle overlap, alternate overlap, or double butt. For closing seams, a variant of the overlap referred to as a "bottom over top shear seam, is used, as well as the double butt seam and a fold over prayer weld. Schematics of these seam constructions and the impact each has on fuel transfer through the fabric are shown in Figures 4.2.4 to 4.2.7.

The shingle overlap is the most common and easiest to fabricate (Figure 4.2.4). As the name suggests, each panel is welded to the next in a shingle style progression. The shingle overlap does, however, leave a potential path for fluid transfer from the inside of the tank to the outside if fuel can transfer through the base fabric and the edges of the panels are not sealed. This pathway is clearly illustrated in the cross sectional shingle overlap in Figure 4.2.4. For any panel (example shown ② and ⑤), one warp panel edge is inside the tank while the other end of the panel is outside the adjoining panel. As the tank is filled

and fuel pressure increases internally above ambient, it creates a slight pressure differential between the inside and outside of the tank. Repeated tank filling and draining, as well as expansion and contraction due to changing daily external temperatures, will allow for fuel to penetrate into any unsealed internal edge.

Figure 4.2.4 – Shingle Overlap Seam and Representative Tank Panel Layout
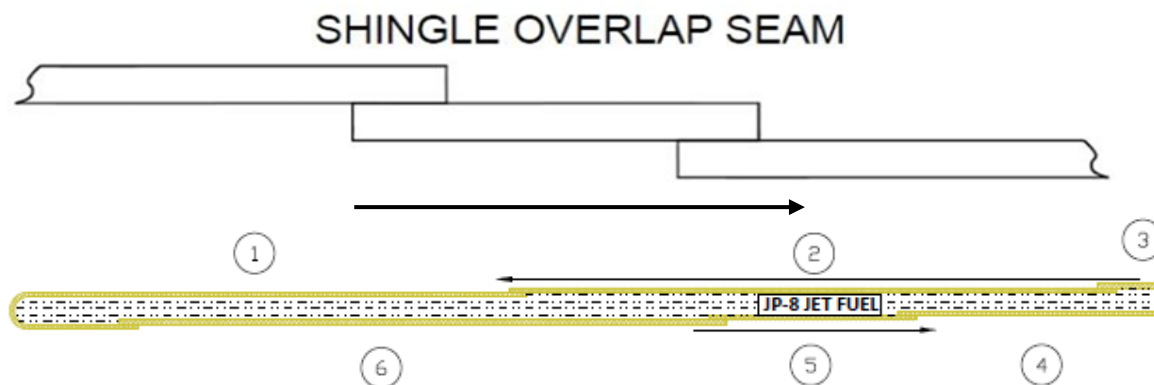
The alternate overlap design helps to eliminate the potential for fuel transfer by not providing an inside to outside pathway (Figure 4.2.5). It is, however, critical to make sure that the alternate progression is maintained throughout the welding process. This "lack of a pathway" is shown in the cross-sectional tank view in Figure 4.2.5. Theoretically, the external panel edges (example ②) will be at atmospheric pressure and the internal panels (example ⑤) will be at equilibrium with the fluid pressure.

Figure 4.2.5 – Alternate Overlap Seam and Representative Tank Panel Layout
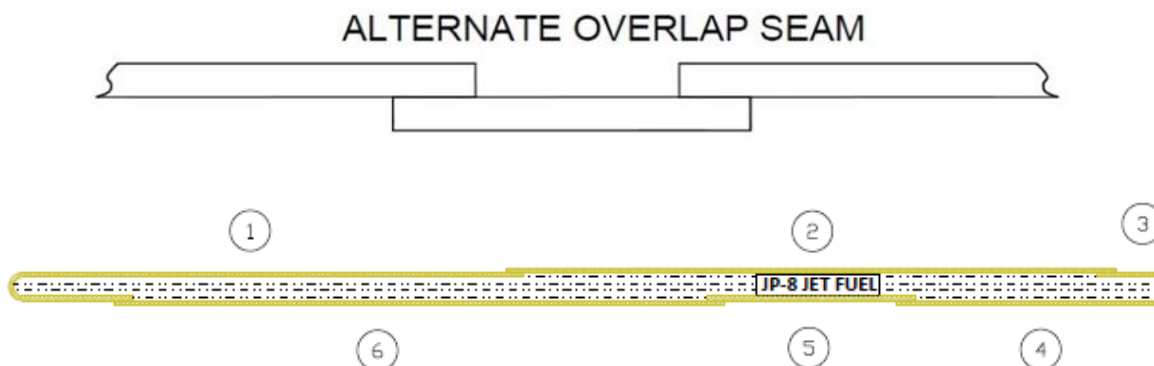
The double butt seam typically takes more time to complete; however, it does have some added benefits (Figure 4.2.6). Like the alternate overlap, the double butt seam greatly reduces the potential pathway through the panel for fluid transfer. In the case of the double butt strap, the panels are sandwiched between two material straps which reinforce the weld area and isolate the panel ends from the fluid.

Figure 4.2.6 – Double Butt Seam and Representative Tank Panel Layout

DOUBLE BUTT SEAM

JP-8 JET FUEL
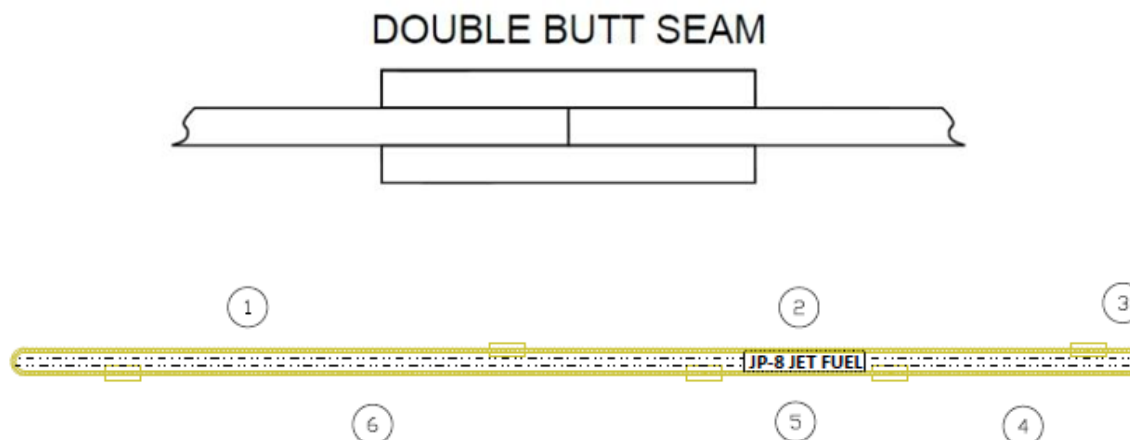
Lastly, there is the foldover prayer weld (Figure 4.2.7). The top panel is welded in peel with the bottom with an offset from the edge of the base material. The top panel is then folded back onto the edge of the bottom flap and shear weld applied to complete the seam. This weld is not shown in a cross-sectional tank view because it typically is used only as a closing seam.

Figure 4.2.7 – Fold-Over Prayer Weld Closing Seam

FOLD OVER PRAYER WELD with TAPE

B

End View

B
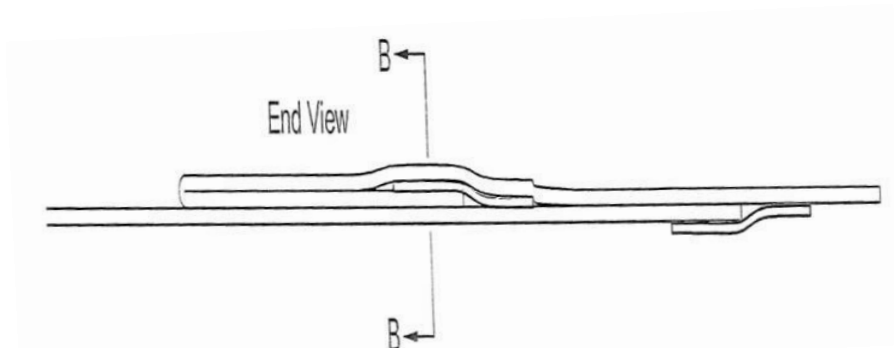
Figure 4.2.8 illustrates the effect of fluid weight on tank stretch in a typical standard design tank. By definition, the hydrostatic pressure exerted by a fluid at equilibrium at a given point will be due to the force of gravity. Hydrostatic pressure will vary throughout the tank in accordance with Pascal's Principle which states:

$$\Delta P = \rho g\,(\Delta h)$$

where:

ΔP = hydrostatic pressure
ρ = fluid density
g = acceleration due to gravity
Δh = height of fluid above measurement point

In a CFT, the material will serve to constrain and counteract the force the fluid exerts. The hydrostatic pressure is generally assumed to act perpendicular to a tangent at any point on the tank inner wall.

Therefore, the resulting fabric tensions will depend on the resultant local force vectors and the tank geometry will alter where the peak stresses occur. By the time the tank reaches 50-75% of its target volume, the material begins to stretch. When filled to its target volume or over-filled, if the periphery of the tank lifts the suspended fluid off the ground, the weight (mg) will need to be supported by increased tension in the fabric (Ft) (Figure 4.2.8). Based on previous testing with a typical standard design tank, greater stress typically occurs on the top, middle of the tank ②.

Figure 4.2.8 – Fluid Weight, Tank Geometry and Impact on Material Stress
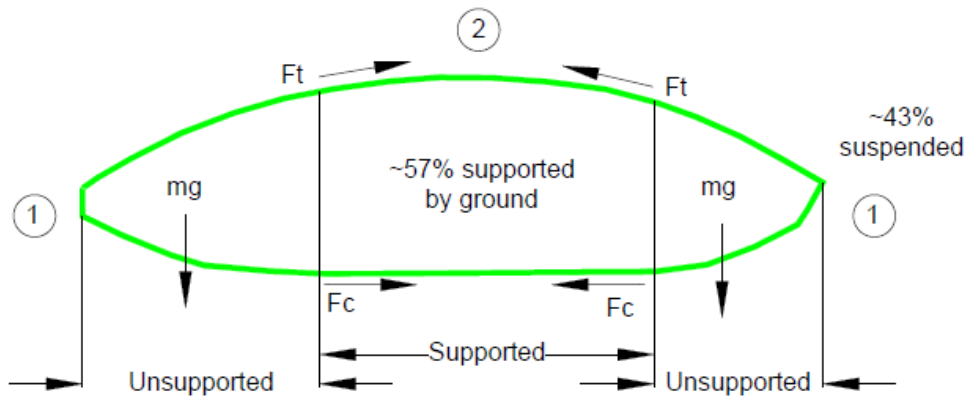
Inherently, if it is possible to keep the base of the tank from lifting off the ground and the periphery from lifting up into the air, even up to 100% of its volume, it is theorized that it may be possible to reduce the stretch and, therefore, the stress encountered in the tank material. This may be accomplished through tank design geometry or additional material. These steps would serve to keep tank height minimized while keeping the tank within the allowable footprint with the majority of the bottom face in contact with the ground. A detailed discussion on the force / mass balance equations is presented in Appendix D.

Another consideration in tank design is the directional nature of the material. Figure 4.2.9 illustrates the difference between the narrow or "fill" direction and the longer or "warp" direction.

Figure 4.2.9 – Warp vs. Fill Directionality of CFT Material
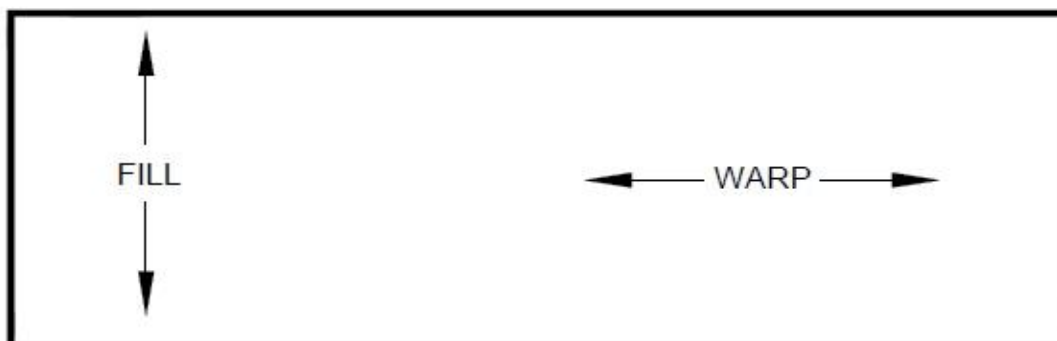
This directionality translates also into a stretch difference, as is shown in the Biaxial Stretch curve in Figure 4.2.10., for a given load, the 1940 PTFF MS 337 coated fabric will stretch two to three times as much in the fill direction as it will in the warp direction.

Figure 4.2.10 – 1940 PTFF Biaxial Stretch Curve
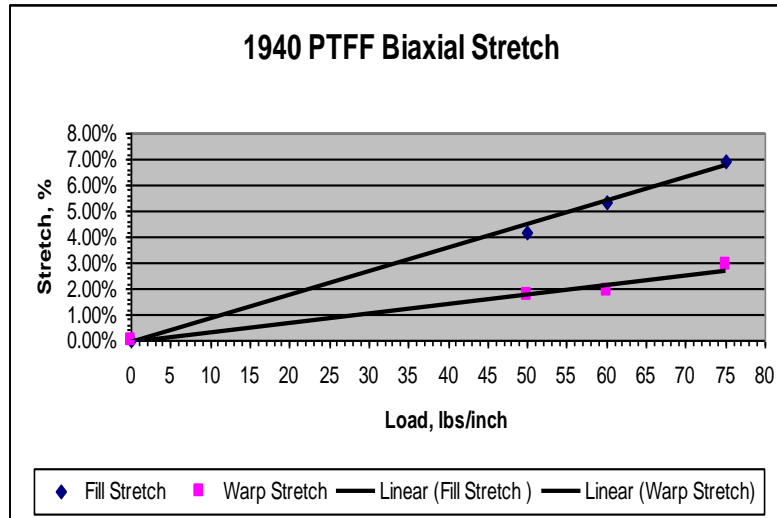
When brainstorming the potential designs for the tank field studies, the directional nature of the material was also considered in terms of what might be done to balance loads and associated stretch.

Collapsible fuel tanks are constructed from a series of welded panels. Although much is known about the characteristics of the single-ply materials, the change in stretch and stress at welds and other tank features is also critical to understanding performance. In an effort to discover the potential impact of different welds, material directionality and multiple plies on tank design, a series of non-traditional Biaxial Stretch tests were conducted with the 1940 PTFF material. For the first test, Biaxial Stretch Test samples were welded for a simple overlap and a double butt seam; then compared to a straight, un-welded material sample. Figure 4.2.11 illustrates the results. The single overlap seam reduces fill stretch by roughly 20% whereas the double butt seam approaches a 30% reduction. There is no noticeable difference between the baseline and overlap warp stretch (i.e., they lie on the same line). However, the double butt seam reduced the warp stretch by as much as 30%.

Figure 4.2.11 – Seam Stretch vs Seam Type
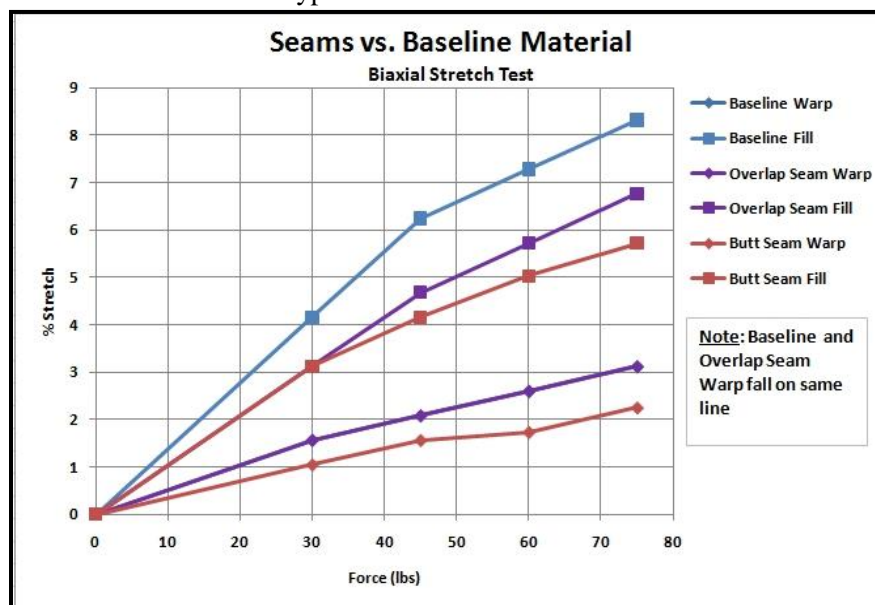
At critical locations on CFTs where fittings are attached, fabricators will typically increase material strength in the area by welding on one or two additional material patches. To further understand the impact of this practice, specifically the combination of material direction and multiple plies, another series of unique Biaxial Stretch tests were run. The results are shown in Figure 4.2.12. The baseline curves again are the single-ply material. A doubler is an area where two plies are welded together while a tripler consists of three (one inside and one outside of a base material). "Uni" refers to unidirectional, indicating that the doubler patch is running in the same direction (i.e., warp aligned with warp, fill with fill), as the base ply. "Bi" refers to bidirectional, or that the patch(es) that oppose(s) the central or underlying base ply.

Figure 4.2.12 – Ply and Directions versus Stretch
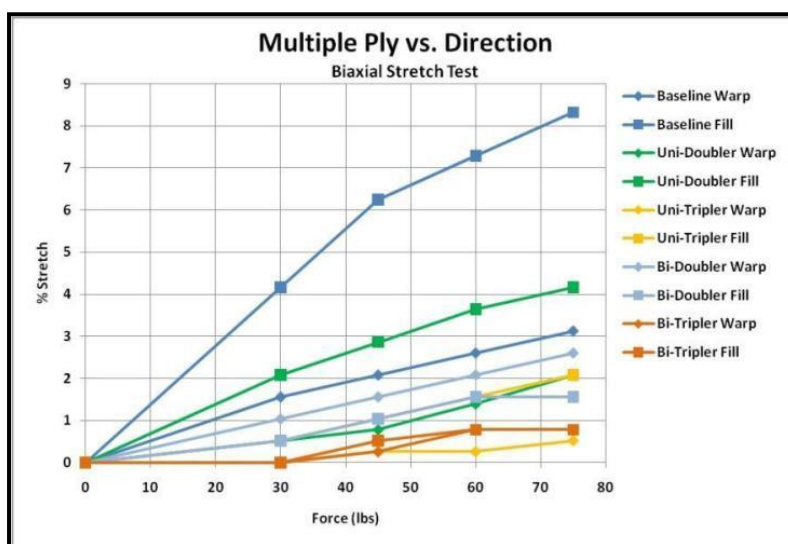
Based on the results shown in Figure 4.2.12, it can be concluded that the net effect of doubling the material is a 50% reduction in fill stretch and slightly less than that for the warp direction. The net effect of the change in direction for the doubler (going from Uni to Bi) is roughly an additional 20% reduction, or ~70% from the baseline. The Uni-Tripler further reduces the stretch seen. The Bi-Directional Tripler gives the most warp and fill stretch reduction with a 90% decrease in both.

4.3   Model Tank Evaluation

In an effort to optimize the field based testing, a number of 1:100 volume scale model tanks were constructed and tested at Seaman Corporation. This included the basic Model Tank (or standard design tank design) from the FY2008 as a baseline. A summary of the fill results is captured in Table 4.3.1. In addition, a series of trapezoidal type tanks, a Quonset hut geometry and two Transverse T variations was fabricated and tested. The tanks were all based on an equivalent starting footprint with a target of 30 gallons at 100% fill volume. Photographs were taken of all tanks when at empty at 15, 30 and 45 gallons or max fill volume from the top of the tank (footprint), warp and fill direction sides. The "Max Fill" volume condition occurred if water overflowed from the tank vent prior to reaching 45 gallons. A spline curve was drawn around the perimeter of each image so that an overlay of the different fill volumes could be created and compared on one page. A grey outline representing a scaled 14 ft x 14 ft estimated footprint and height envelope was added for spatial reference. A spline color code key was developed, so that the progression of the tanks directional expansion during fill could be visualized. The key is shown in Table 4.3.0.

Table 4.3.0 - Fill Key

Grey	14' x 14' Scaled Envelope
Yellow	Empty
Blue	15 gallons
Green	30 gallons
Magenta	30 gallons, <45 gallons – fill aborted, water out of vent port
Red	45 gallons

The changing footprint and profiles of the tanks throughout the "fill to maximum" was of particular interest. It became evident that certain geometries were better at keeping the entire tank footprint on the ground compared to others. This is clearly illustrated when comparing Tank 9 (Trap 4 – welded corners) versus Tank 3(TK3K2 – FY2008 standard design tank design). Tank 4 and Tank 5 were early attempts at understanding the impact of a trapezoidal side profile alone. While both designs had some influence on keeping the fluid on the ground, keeping the entire tank footprint on the ground was not optimized until the trapezoidal corners were welded together (as in Tank 9). Furthermore, unique concepts such as the Quonset hut design were proven in a scale model design. These scale model studies supported the concept of some of the fundamental design geometries implemented in the full scale field test.
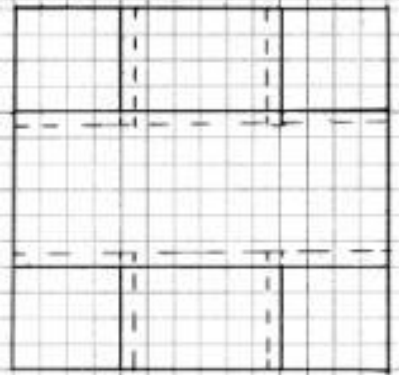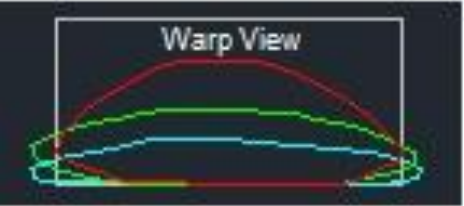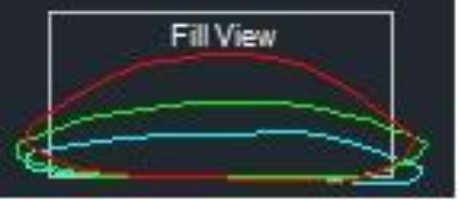
Table 4.3.1 - Model Tank Fill Profiles
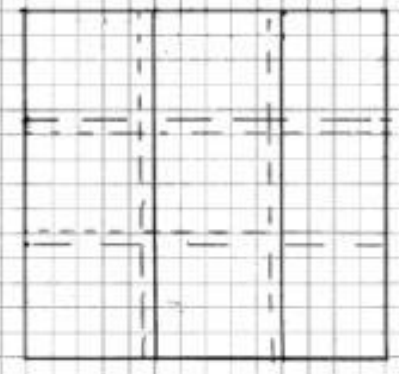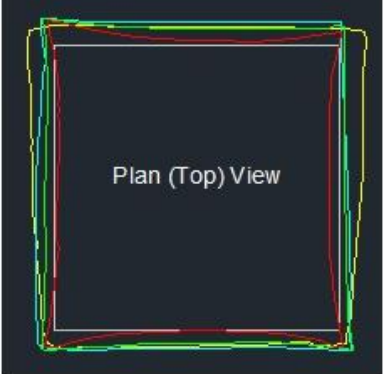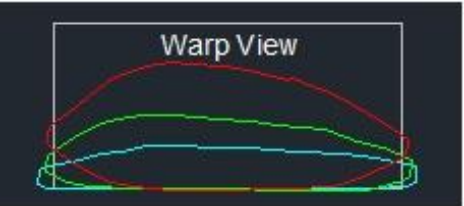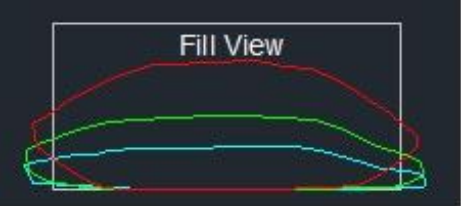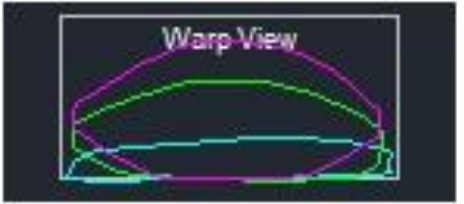
Tank Description	Tank Fill Volume (gal)	Tank Design	Plan (Top) View	Warp View	Fill View
Tank 1 Transverse T	0 15 32.2 45				
Tank 2 Inverse Transverse T	0 15 30 45				
Tank 3 TK3K2	0 15 30 35.7				

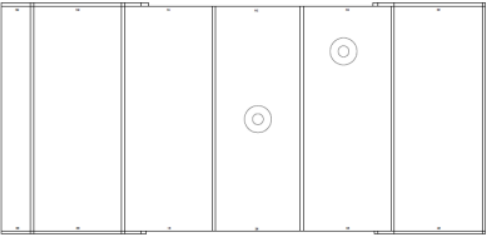Table 4.3.1 - Model Tank Fill Profiles (con't)
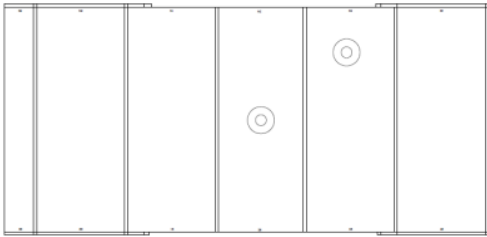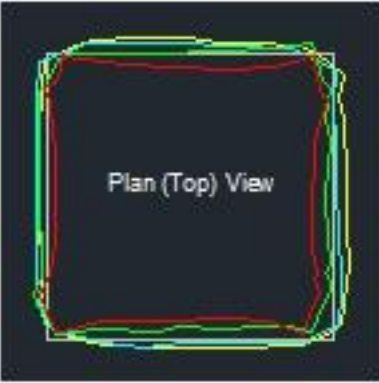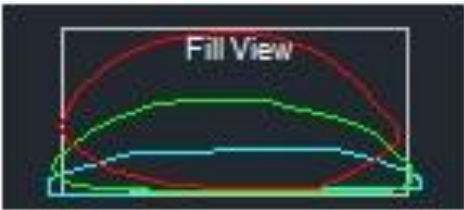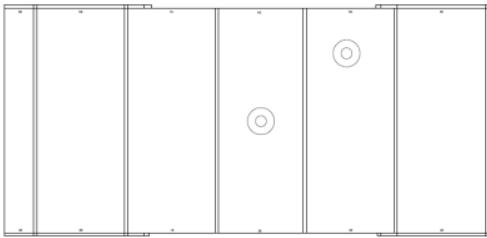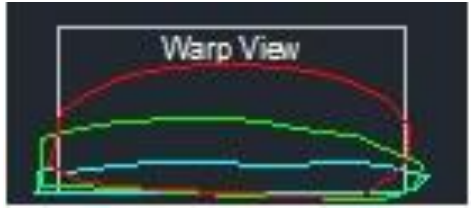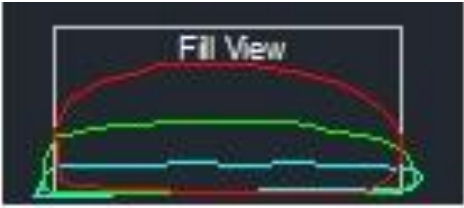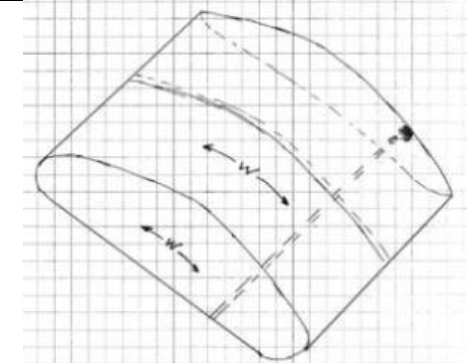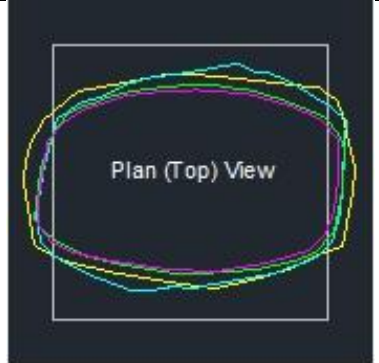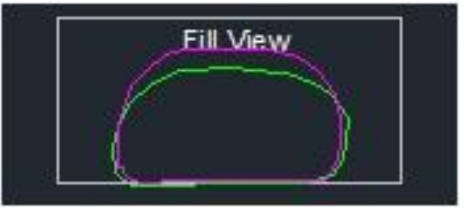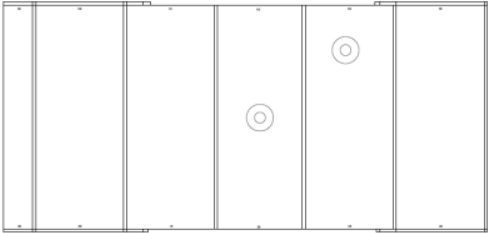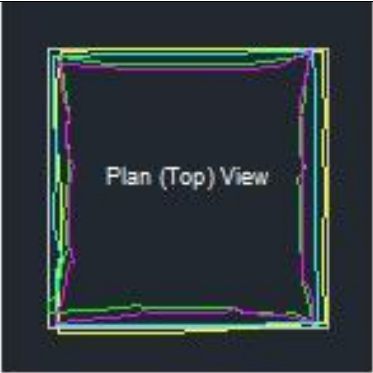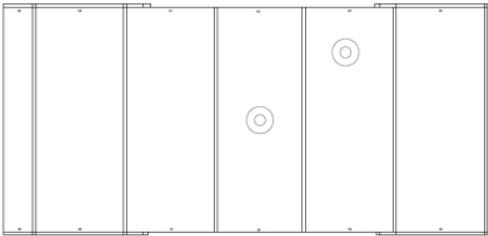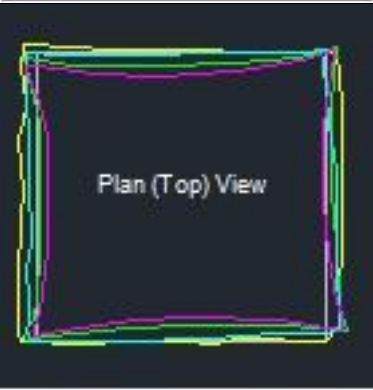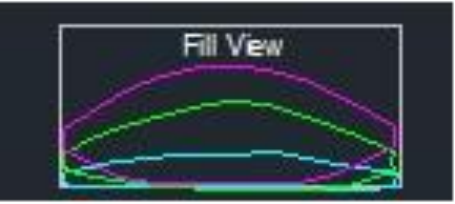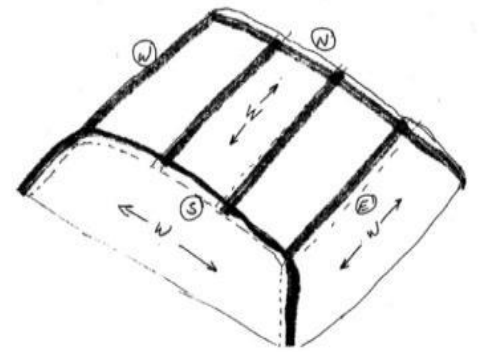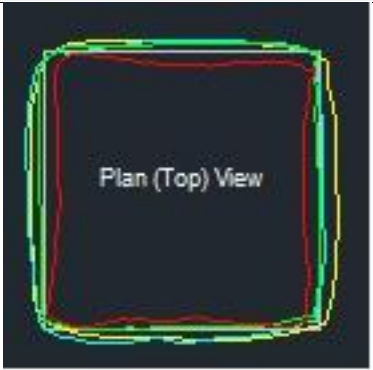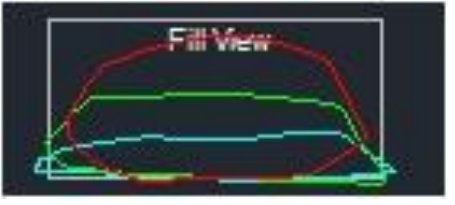
Tank Description	Tank Fill Volume (gal)	Tank Design	Plan (Top) View	Warp View	Fill View
Tank 4 Trap 2 (trap corners not welded)	0 15 30 45				
Tank 5 Trap 4 (trap corners not welded)	0 15 30 45				
Tank 6 Quonset Hut	0 15 30 32.3				

Table 4.3.1 - Model Tank Fill Profiles (con't)

Tank Description	Tank Fill Volume (gal)	Tank Design	Plan (Top) View	Warp View	Fill View
Tank 7 TK3K2 3425	0 15 30 31.5		Plan (Top) View	Warp View	Fill View
Tank 8 TK3K2 scaled	0 15 30 33		Plan (Top) View	Warp View	Fill View
Tank 9 Trap 4 (with welded trap corners)	0 15.2 30 45		Plan (Top) View	Warp View	Fill View

A series of four, five-inch square measurement panels were drawn onto each tank (see Figure 4.3.1) and stretch measurements in both the warp and fill directions were recorded. Each tank was plotted at volume fill levels of 15, 30 and 45 gallons (or maximum fill) along with the associated warp and fill stretch measurements.

Figure 4.3.1 – Model Tank Top Panel Showing 4 Measurement Panels

A few interesting trends appeared in this data. Both the Tank 4 and Tank 5 trapezoids (Figures 4.3.5 and 4.3.6) did not show any significant reduction in warp (~2%) or fill stretch (~4-5%). However, Tank 9 (Figure 4.3.10), with the welded corners maintained both warp and fill at reduced stretch levels (<1.5%). This design, based on the geometry of a truncated frustrum, appeared optimal because it kept the base on the ground at 100% volume in both warp and fill views while keeping the stretch impact minimal.

The Quonset Hut design also indicated a positive result, for both the warp and fill profile as well as the associated stretch results (Figure 4.3.7 – Tank 6). The final severe upward tick of the fill stretch from 1.25% to 2.5% across the last 2.3 gallons of volume was typical of any model tank where the tank maximum volume was reached before 45 gallons (Figures 4.3.4, 4.3.7, 4.3.8 and 4.3.9 – graphs of Tanks 3, 6 , 7 and 8).

Figure 4.3.2

Tank 1 - Transverse T

Figure 4.3.3

Tank 2 - Inverse Transverse T

Figure 4.3.4

Tank 3 - TK3K2 (2619)

Figure 4.3.5

Tank 4 - Trap 2
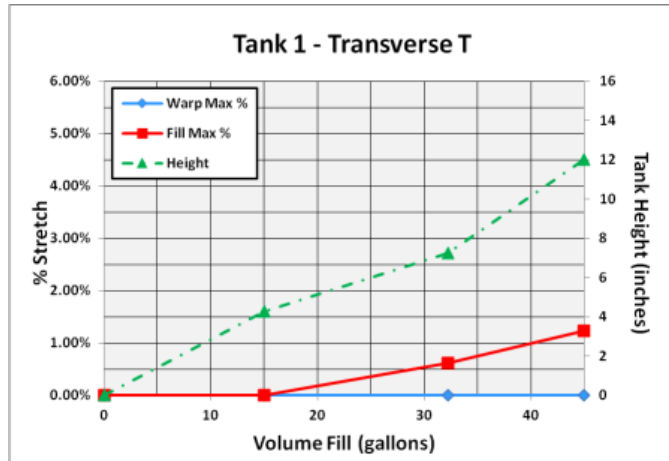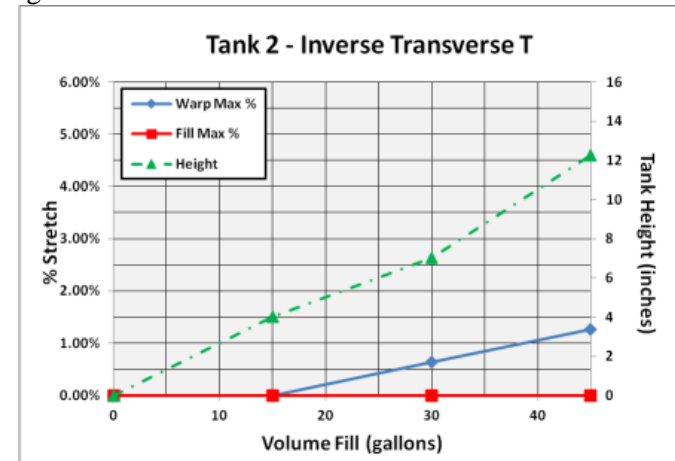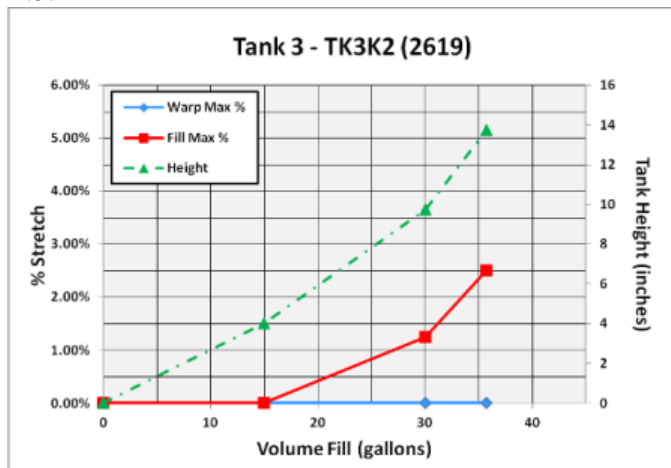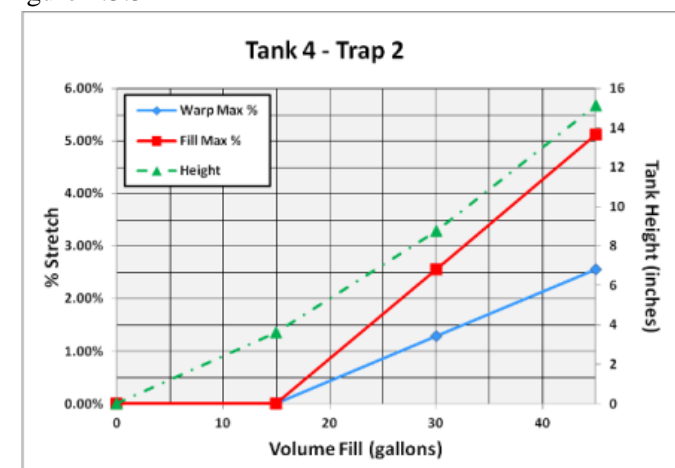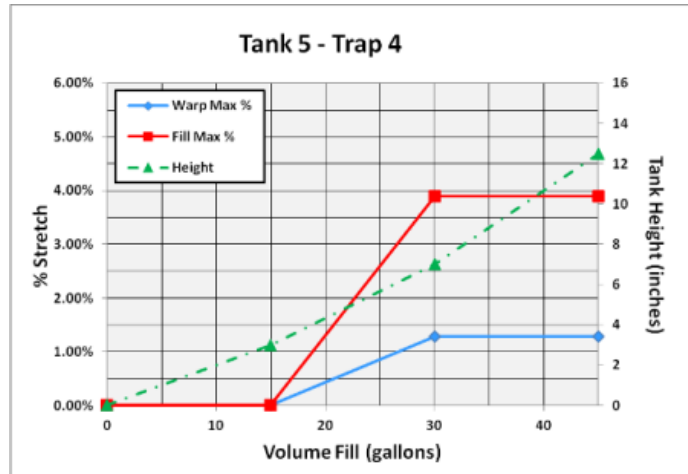
Figure 4.3.6
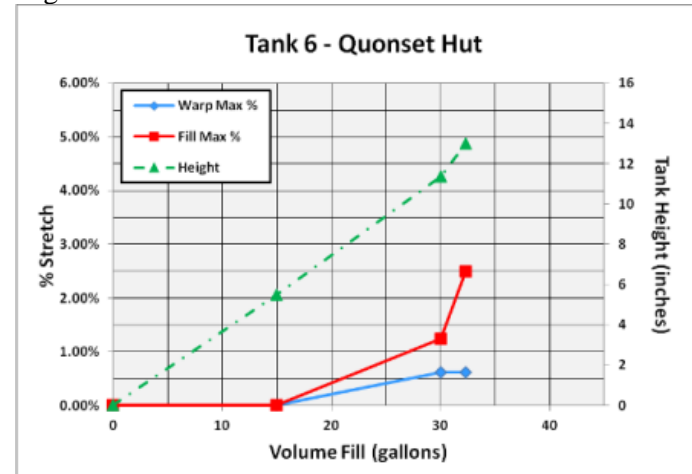
Figure 4.3.7

Figure 4.3.8
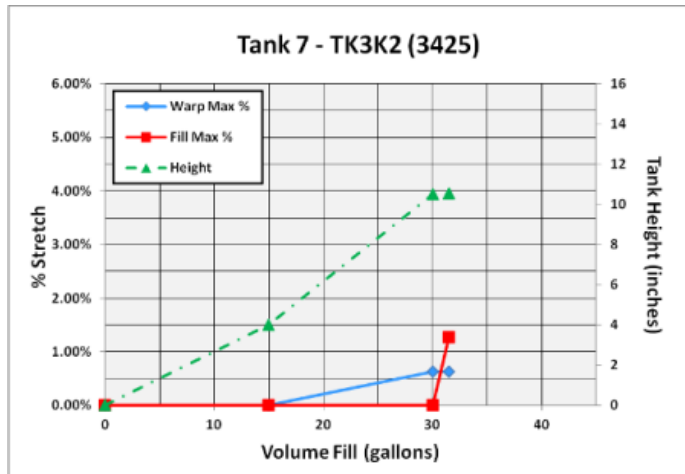
Figure 4.3.9
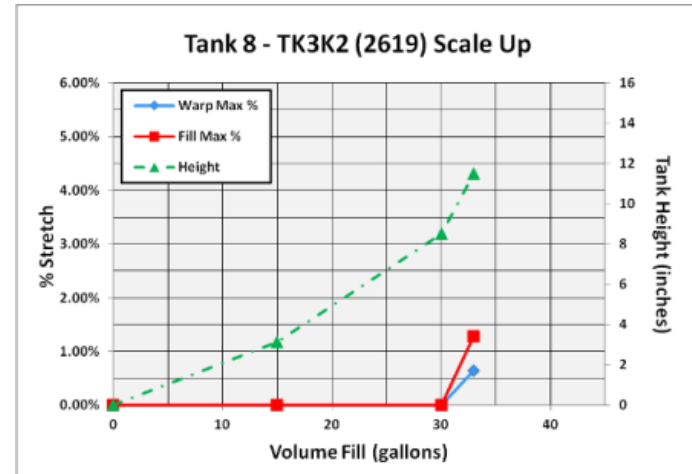
Figure 4.3.10
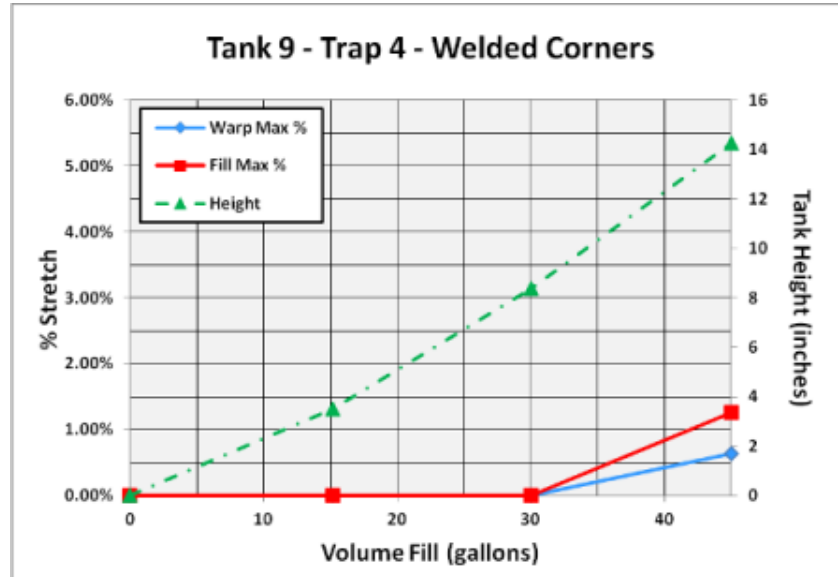
4.4   Field Test Tank Designs

4.4.1   Quantity Determination

The Model Tank testing in FY2008 program (Contract No. SP0600-04-D-5442, Delivery Order 1017, Section 8.0), verified that it is possible to create stresses seen in much larger tanks (e.g., 50,000 – 210,000 gallons) through controlled overfilling of 3,000 gallon tanks. The team created a list of tank design features to evaluate as a result of careful review of reported tank field failures, issues that surfaced during the Technical Roundtable and the tank design FTA and FMEA efforts. To maintain a baseline comparison to the FY2008 results, Seaman decided to use the full panel width Model Tank 2 as a basic design for the FY2009 field testing. For comparison purposes, a determination was made that it would also be important to have representative fabricators' designs as part of the study. Seaman Corporation created a number of unique prototypes that embody tank design changes to reduce stress and improve overall performance.

While several government, military, and commercial sites were considered, the Southwest Research Institute (SwRI) was selected as the preferred test site. SWRI was selected based on cost, ease of logistics, easiest adaption for the needs of this test, flexibility in testing and overall experience and comfort with working with JP-8. SwRI had an unused ~200 ft x 200 ft bermed area that was determined ideal for this test. Based on the bermed area size, it was determined that it would be possible to operate up to 20, 3,000 gallon tanks. This left room for a 50,000 gallon tank that would be used to verify stretch at 100% fill volume as well as a central safety tank.

From all of the design inputs, a list of tank features for evaluation in the field test tanks was assembled. This list was broken down as depicted in Table 4.4.1:

Table 4.4.1 – Field Tank Features Summary

Tank Feature	Feature Description
Panel Seam Type	Shingle Overlap
	Alternate Overlap
	Double Butt Seam
Closing Seam Type	Bottom Over Top Shear Seam
	Double Butt Seam
	Fold Over Prayer Weld
	Shingle Overlap w/ T Seams
Corners	Tapered Triangle
	Square Welded - No Clamp
	Square Welded w/ Clamp
	Semicircular Cap
	No Corners Present
	Trapezoidal Angle
Fittings	Standard
	Bidirectional Doubler
	Bidirectional Tripler
	O-Ring Compression
	Per Fabricator
Seam Tape	Standard
	Butt Seam
	1" Reinforced
	2" Reinforced
	Profile

The options in Table 4.4.1 served as the basis for the 20 tank designs to be fielded. The panel seam types were previously discussed in Section 4.2.

It was determined that the wide variation in tank features could be best represented by splitting the tank types into the 3 categories: 1) 6 – Fabricator; 2) 8 – FY2008 design; 3) 6 – Seaman prototype designs. An even number of tanks was maintained in each category to allow for matched pairs and ease in shuttling during over-fill. Special care was taken to minimize the number of feature design changes between tanks, especially with the baseline 8 - FY2008 tanks. Both the fabricator and the Seaman prototypes provided additional tank features for evaluation.

Table 4.4.2 summarizes the 20 tank design features along with the additional specific information that will be valuable when evaluating the field test results. Included on Table 4.4.2 are quantities, such as the number of panels and their total seam length, number of closing seams and their lengths, the number of T-seams, and the number of corners present. This additional information will be critical when evaluating tanks by establishing a basis for normalizing their performance.

Table 4.4.2 – Final Plus-Up Tank Farm Design List

Tank #	Tank Design	Total Panels			Closing				Corners		Fittings	Seam Tape
		Type	#	Panel Seam Length (ft)	Type	#	Length (ft)	# of T-Seams	Type	#	Type	Type
50	Fabricator	Shingle Overlap	Per Fabricator		Bottom Over Shear Seam	2	Per Fabricator		Tapered Triangle	4	Per Fabricator	Per Fabricator
10 / 11	Fabricator	Shingle Overlap	Per Fabricator		Bottom Over Shear Seam	2	Per Fabricator		Tapered Triangle	4	Per Fabricator	Per Fabricator
12S	Fabricator	Per Fabricator	Per Fabricator		Per Fabricator	2	Per Fabricator		Per Fabricator		Per Fabricator	Per Fabricator
13	Fabricator	Alternate Overlap	Per Fabricator		Bottom Over Shear Seam	2	Per Fabricator		Per Fabricator	4	Per Fabricator	Per Fabricator
14 / 15	Fabricator	Double Butt Seam	Per Fabricator		Double Butt Seam	2	Per Fabricator		Square Welded Corner with Clamp	4	Standard	Butt Seam
16	TK3K2 Phase I	Shingle Overlap	6	84	Bottom Over Shear Seam	2	28	12	Square Welded Corner with Clamp	4	Standard	Standard
17		Alternate Overlap										Profile
18		Shingle Overlap	6	84	Bottom Over Shear Seam	2	28	12	Square Welded Corner with Clamp	4	Bidirectional Doubler	1" Reinforced
19		Alternate Overlap									O-Ring Compression	2" Reinforced
20		Alternate Overlap	6	84	Fold Over Prayer Weld	2	28	12	Square Welded Corner with Clamp	4	Standard	Standard
21		Shingle Overlap			Fold Over Prayer Weld						Bidirectional Tripler	Profile
22		Double Butt Seam	6	84	Double Butt Seam	2	28	12	Square Welded Corner with Clamp	4	Bidirectional Doubler	Butt Seam
23											O-Ring Compression	
24	Canoe Ends	Shingle Overlap	5	97	Shingle Overlap w/ T-Seams	1	5-1/2	6	Semicircular Cap	4	Bidirectional Tripler	1" Reinforced
25	Belly Band	Alternate Overlap	6	56	Shingle Overlap w/ T-Seams	2	113	9	No Corners Present	0	Standard	Profile
26	10 Panel Trap	Shingle Overlap	10	104	Shingle Overlap w/ T-Seams	4	52	8	Trapezoid Angle	4	Standard	1" Reinforced
27	Quonset Hut	Shingle Overlap	5	148	Double Butt Seam	1	14	6 - 8	No Corners Present	0	Bidirectional Tripler	Butt Seam
28	6 Panel Trap "Dog Bone"	Alternate Overlap	6	77	Shingle Overlap w/ T-Seams	4	65	8	Trapezoidal Angle	4	O-Ring Compression	2" Reinforced
29	Transverse T	Alternate Overlap	4	53	Double Butt Seam	3	42	8	Square Welded Corner with Clamp	4	Standard	Butt Seam

In addition to evaluating the tank material, an effort was also made to evaluate two other critical components to the tank fabrication: the fittings and the seam tape used for sealing the scrim edge.

4.4.1.1 Manway / Discharge Fittings

For the manway / filler / discharge and vent fittings, either a standard, fabricator specified, a prototype O-ring compression style or a Bi-Directional Doubler or Tripler (discussed in Section 4.2) was used. Figures 4.4.1 and 4.4.2 depict an installed prototype O-ring compression fitting with the second O-ring sandwiched between the two inner oval closure rings. For Tanks 19, 23 and 28, this was done on the manway / filler / discharge port and the air vent. No drain assemblies were used on any of the tanks because they were considered a potential leak source that would be hard to detect and evaluate on a field tank.

Figure 4.4.1 – O-Ring Compression M/F/D Fitting

Figure 4.4.2 – O-Ring Compression Fitting Close Up
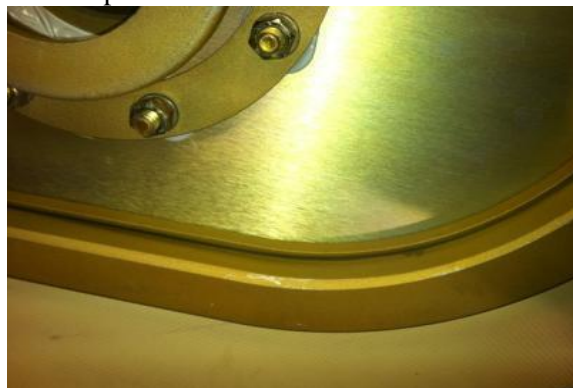
4.4.1.2 Seam Tapes

Five types of tape were chosen for evaluation in the seam area for the program. The standard 1"
polyurethane film tape was used to establish a baseline for comparison. For the double butt seams, a 4"
wide fabric reinforced sealed tape was utilized on both the inside and outside of the seam (Figure 4.4.3).
Three unique prototype tapes were also included a 1" (Figure 4.4.4) and a 2" (Figure 4.4.5) fabric
reinforced sealed tape and a stepped profile tape. The profile tape which consists of a 1" film strip offset
on the edge of a 2" sealed fabric tape (Figures 4.4.6 and 4.4.7). The fabric reinforcement is depicted as the
thick dark line shown in the middle of each cross-sectional view with the sealed coating compound
around the exterior for each tape.

Figure 4.4.3 – 4" Reinforced Sealed Tape Cross-Sectional View

4" long x 0.040" thick thermoplastic polyurethane coated tape   0.007" internal fabric reinforcement
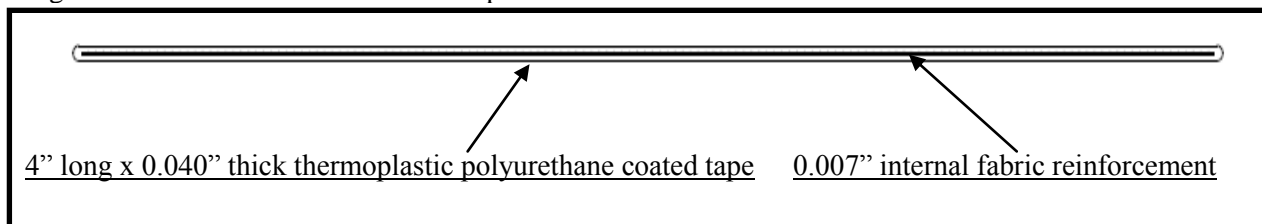
Figure 4.4.4 – 1" Reinforced Sealed Tape Cross-Sectional View

1" long x 0.040" thick thermoplastic polyurethane coated tape   0.007" internal fabric reinforcement
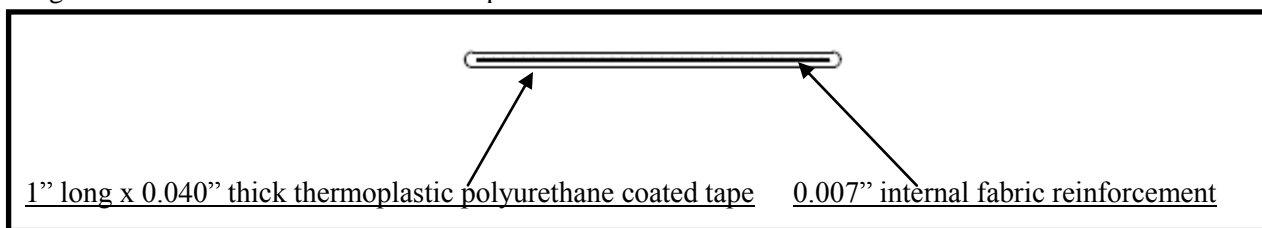
Figure 4.4.5 – 2" Reinforced Sealed Tape Cross-Sectional View

2" long x 0.040" thick thermoplastic polyurethane coated tape   0.007" internal fabric reinforcement
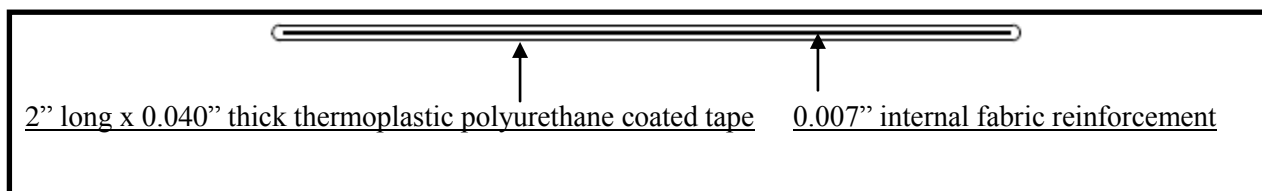
Figure 4.4.6 – 1" PRF Tape – Cross-Sectional   Figure 4.4.7 – 1"PRF Tape – Rendered
View
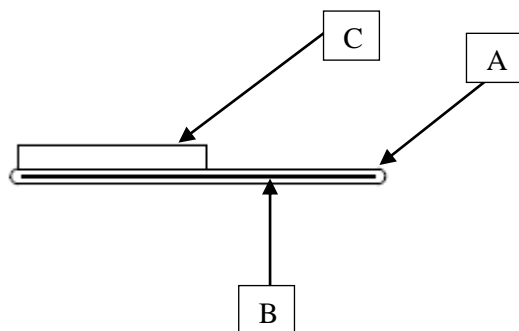
1" long x 0.040" thick thermoplastic
polyurethane   (TPU) coated tape (A)
0.007" internal fabric reinforcement (B)
and ½" long x 0.060" thick TPU film (C)
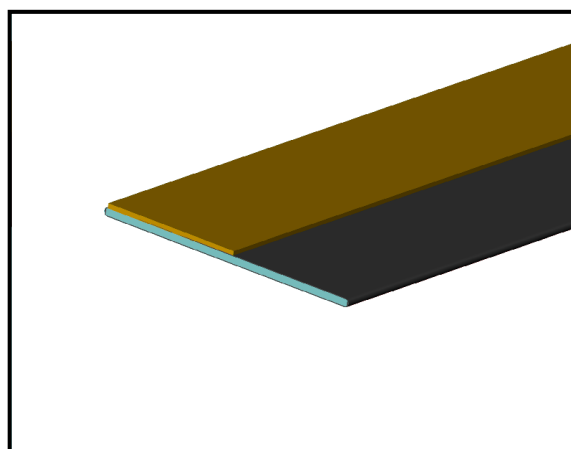
Initial testing of weld adhesion for both Hot Air and Radio Frequency welding of the prototype tapes proved successful with values which approached $20 lbs_f$/in repeatedly. However, this was only tested on a straight panel seams. When it came to working the tape around curved profiles and across multiple plies on closing seams, adherence was not as consistent. The fabricators indicated that a rougher surface texture and a reinforced fabric tape that stretched more would possibly help with more consistent weld flow and adhesion.

4.4.2   Fabricator Designs

Tanks 10 – 15 were dedicated to fabricator designs (Fabricator A & B) in an effort to establish a comparative baseline against which the other tanks and their feature might be evaluated. The two fabricators have a long history of successfully producing collapsible fuel tanks for the U.S. Military. However, their approaches to tank design and fabrication are quite different. Tanks 10, 11, 12S and 13 are either their current or potential future commercial designs or are patent protected.

4.4.2.1 Fabricator A Standard Tank

The standard design provided by Fabricator A relies on tapered panels and triangular corner patches to create a unique tank shape (Figures 4.4.8 and 4.4.9). The tank uses slightly less material and creates a tank footprint which is less than the 14 ft x 14 ft footprint of the typical standard design tank when filled to 3,000 gallons. At the 3,000 gallon target, however, it is taller in height than a typical standard design tank.

Figure 4.4.8 – Fabricator A Tank – Warp Side View

Figure 4.4.9 – Fabricator A Tank – Fill Side View

4.4.2.2 Fabricator B Standard Tank

Fabricator B provided a design that is more representative of a typical standard design tank overall. They do have a number of unique features relative to fitting and closing seams (Figures 4.4.10 and 4.4.11).

Figure 4.4.10 – Fabricator B Tank – Warp Side View

Figure 4.4.11 – Fabricator B Tank – Fill Side View – Background Filled Tank

4.4.2.3 Fabricator B Double Butt Seam Tanks

At the request of Seaman Corporation, Fabricator B provided a standard design tank design based on the use of double butt seams for both the warp panel and closing seams (Figures 4.4.12 and 4.4.13). Tanks 14 and 15 were fabricated using the double butt seams for both the warp panel and closing seams.

Figure 4.4.12 – Double Butt Seam Tank – Warp Side View

Figure 4.4.13 – Double Butt Seam Tank – Fill Side View

4.4.2.4 Fabricator B Prototype Tank

Fabricator B requested adding a prototype tank design to the study that was reviewed and approved by the study sponsor, DLA. The tank is typical in its pillow shape, however, the body is made from a continuous panel which is welded to itself on a slight angle (Figures 4.4.14 and 4.4.15).

Figure 4.4.14 – Prototype Spiral Tank – Warp Side View

Figure 4.4.15 – Prototype Spiral Tank – Fill Side View

4.4.3   FY2008 Program Design

The FY2008 Program baseline design and associated testing is discussed at length in the final report (Section 7.0). A total of eight different tanks based of the original full panel design (Tank 2) with variations in panel seams, closing seams, corners, fittings and seam tape type were designed and fabricated for field testing. Figure 4.4.16 shows the basic design layout for this style of tank. Refer to Section 4.2, where fabrication of this type of standard design tank was covered).

Figure 4.4.16 – Typical Standard Design tank showing elevated corners and ends
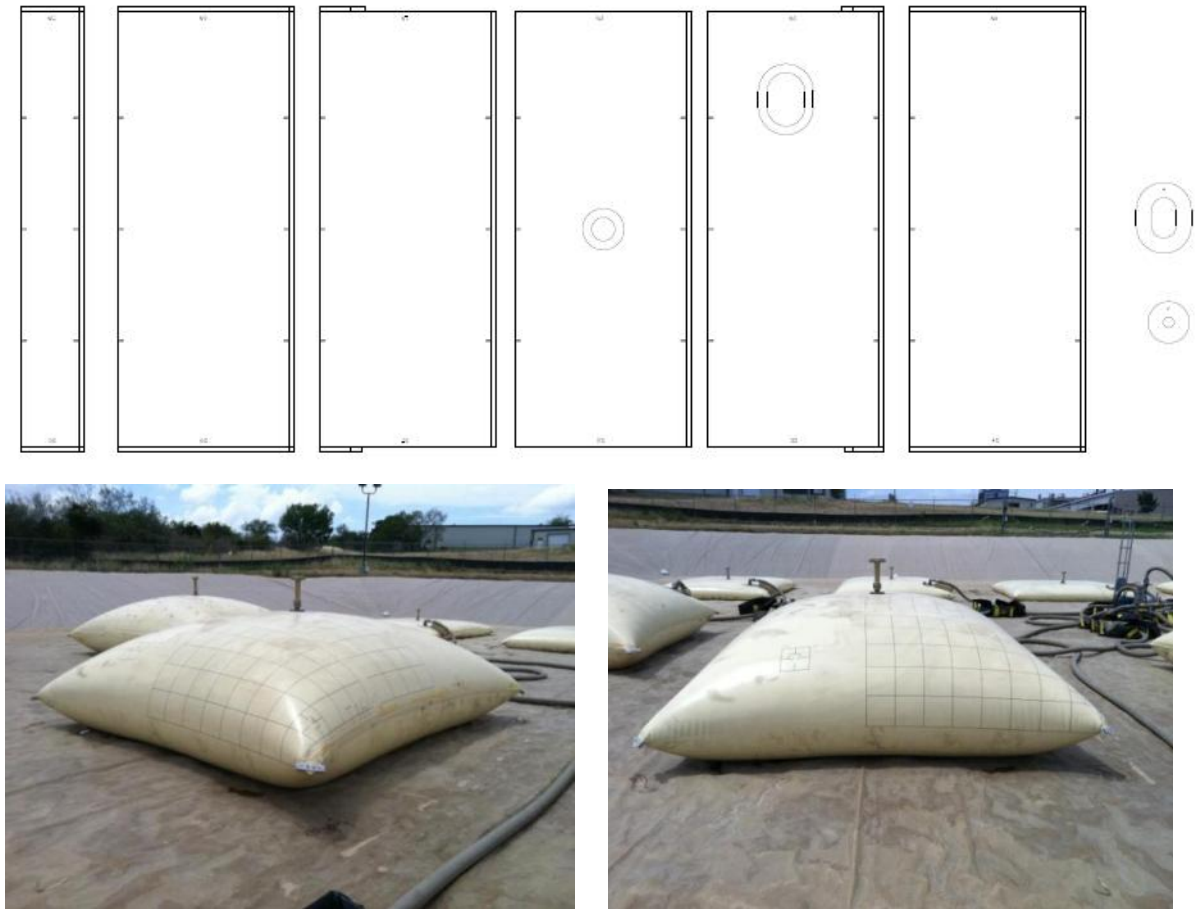
4.4.4   Prototype Tank Designs

Canoe Ends Design (Figure 4.4.17)

This design features unique "canoe" shaped panels that form the end closing seams. For each end, two canoe shapes are welded to each other with a simple overlap weld that forms a pocket. The two canoe pockets are then joined to each other by an overlap or double butt seam that is welded to the center continuous panel along both sides of its warp edge. A final closing seam is created between the ends of the center panel(s) on the bottom of the tank. The design of this tank allows the user to increase the tank size with minimal effort. A larger tank may be produced by simply increasing the length of the canoe pockets along the warp direction and adding multiple longer continuous center panels that can be welded in to form a blanket. Even in a 50% overfill condition (4,500 gallons) as shown in Figure 4.4.17, the majority of the tank base remains on the ground when compared to the traditional standard design tank. This tank exhibits the lowest fill height at maximum over-fill of all tanks and the lowest stretch. There are only 6 "T" seams on this tank, where the canoe ends join to the center panel and the ends of the closing seam where it meets the canoe ends on the bottom.

Figure 4.4.17 – Canoe Ends Design, Corner and End Fill Photographs
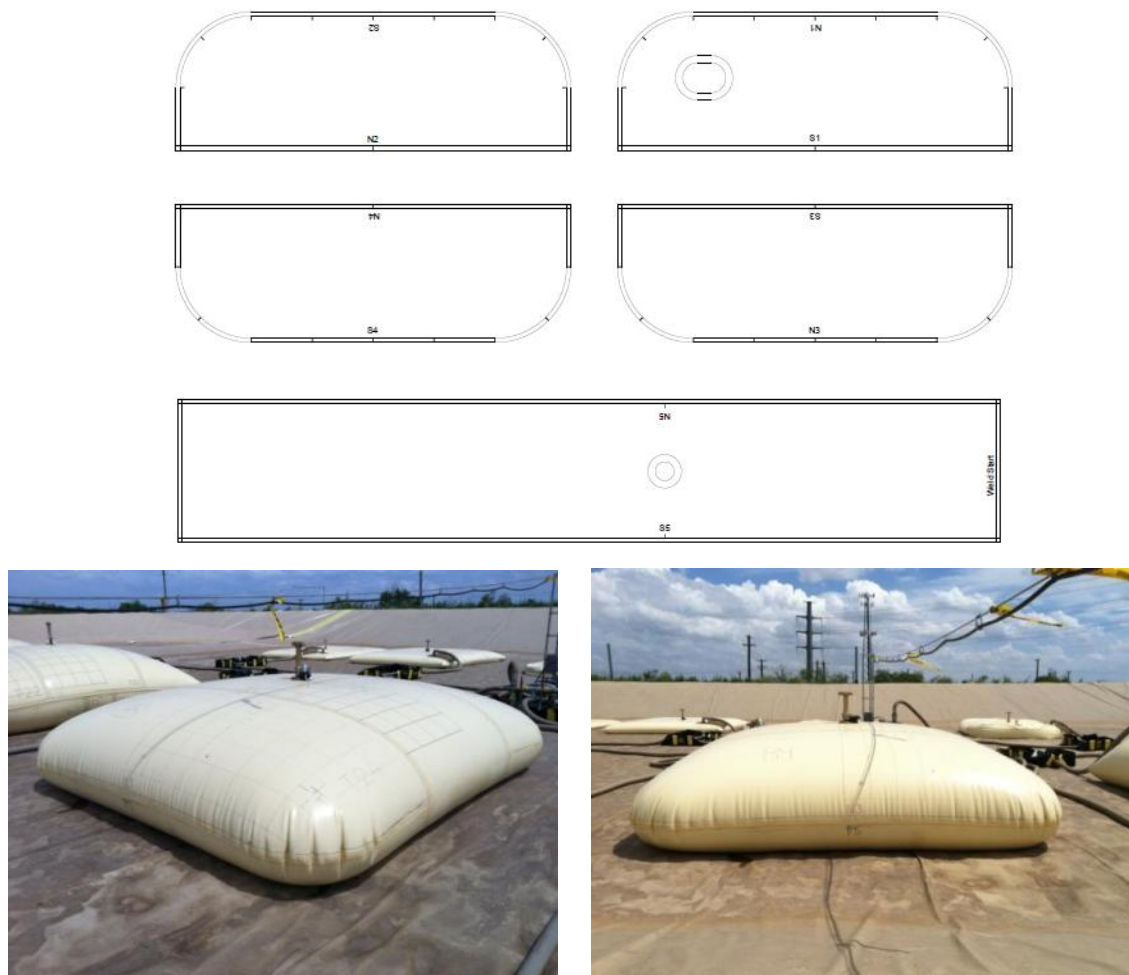
Belly Band Design (Figure 4.4.18)

This simple design consists of upper and lower blankets that are joined by a "belly band" around the circumference. The belly band is closed with a single weld which runs vertically. During fabrication, it does not lend itself to ease of material handling since the continuous weld of the belly band to the top and bottom blankets incur severe material handling issues. If the feed rates vary between the belly band weld to the top versus the bottom blanket, a counter twist between tank top and bottom could be introduced potentially causing the tank to become unstable when filled with fluid. Based on their experience with similar geometries, the fabricator who welded this tank felt that 3,000 gallons is maximum volume allowable for this design.

Figure 4.4.18 – Belly Band Design, Corner and End Fill Photographs
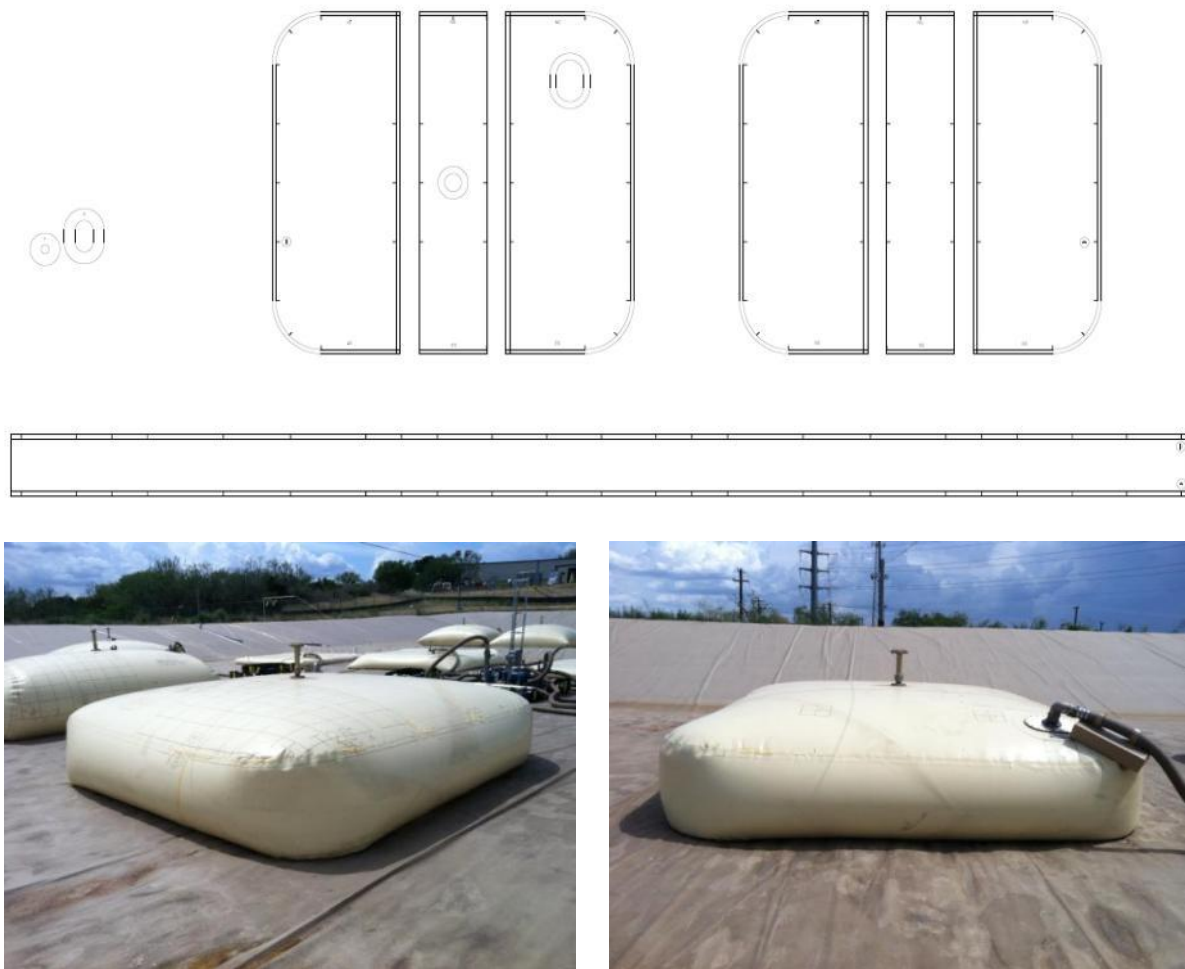
10-Panel Trapezoid Design (Figure 4.4.19)

Both trapezoid designs are exceptional at keeping the corners of the tank on the ground even in a 50% overfill state as shown below (4,500 gallons). The 10-panel trap design is based on the welding together of three top, three bottom and four trapezoidal sides. When filled, the resultant shape can best be described geometrically as a frustum from a square pyramid. The 10-panel trap design increases the number of welds necessary to complete the fabrication. The increased number of weld seams in turn increases the probability of a leak and becomes more labor-intensive to fabricate. Regardless, lower stretch is measured on its top panels. In addition, the side trapezoidal panels do not experience increased stress over a traditional standard design tank.

Figure 4.4.19 – 10 Panel Trapezoid Design, Corner and End Fill Photographs
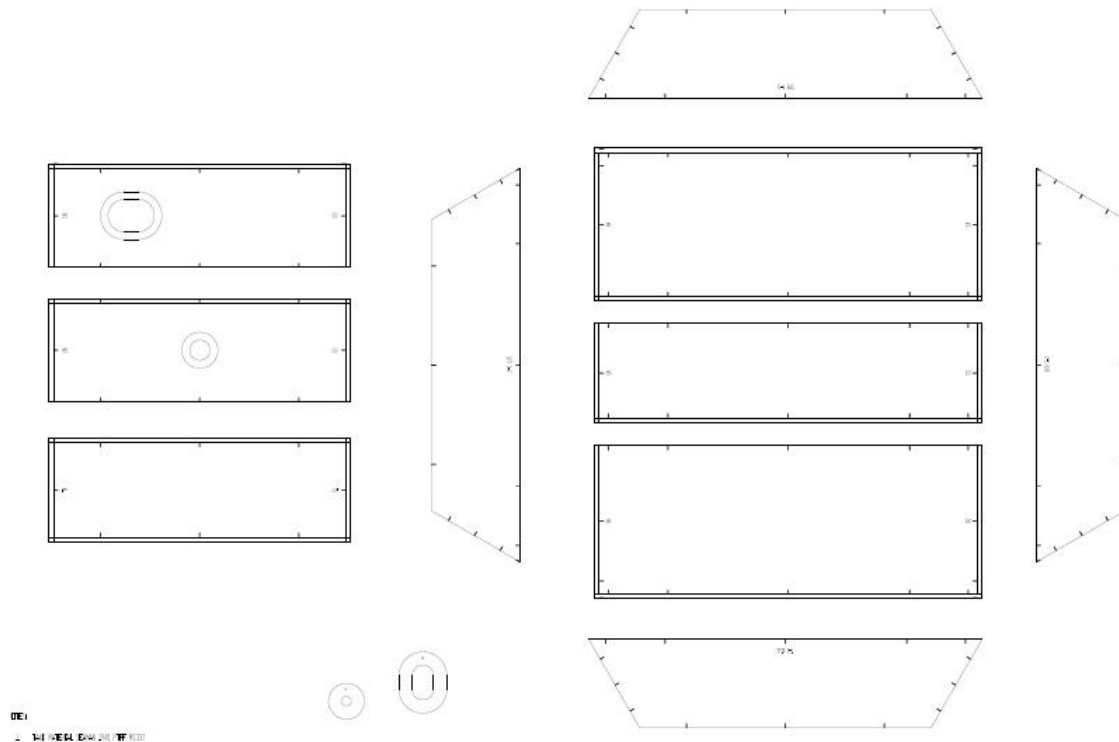
Quonset Hut Design (Figure 4.4.20)

The Quonset hut tank is the greatest departure from the generally accepted tank shapes. When filled, the Quonset hut design resulted in a taller tank with a rectangular footprint. This is due to the need for a liberal radius on the kidney-shaped end panels to promote easy welding without material puckering. This tank could also be scaled up as long as the end panels have a two- to three-foot minimal radius and the height of the panel does not exceed the fill width of currently available material. To keep the tank from bowing out on these ends, the center panels form an hour-glass shape that helps pull the ends in at the top. There is one central closing seam across the bottom of the tank running from end panel to end panel.

Figure 4.4.20 – Quonset Hut Design, Corner, End and Side Fill Photographs
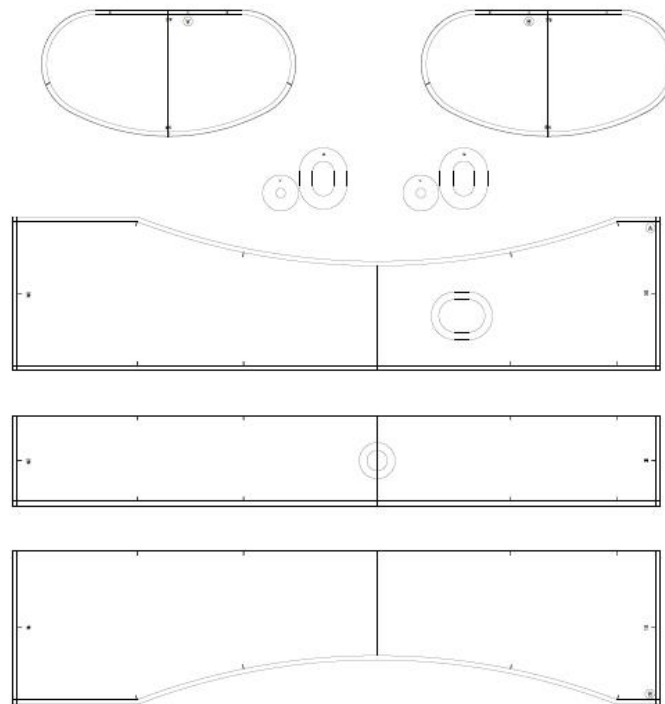
Dog Bone Trapezoid Design (Figure 4.4.21)

The Dog Bone Trapezoid addresses a number of the fabrication and seam issues associated with the 10-Panel Trapezoid design while maintaining certain advantages. The design is referred to as "dog bone" due to the shape the top blanket forms. The bottom panel forms a tapered, dual-sided arrow head. The Dog Bone design also has another distinct feature of balancing warp versus fill stretch directions by offsetting the top and bottom assemblies by 90° (as illustrated in the hand sketch insert upper right in Figure 4.4.21). Instead of 10 separate panels with 20 distinct weld seams, the Dog Bone Trapezoid design requires only eight welds. Fabricating the top and bottom panels separately then welding the periphery is not recommended for this tank because doing so leads to material management issues. It was found that adding the outer dog bone-shaped top end to the bottom blanket first, then closing by adding the top center panel, is much more efficient. Also it can be readily scaled up to much larger tank sizes by simply increasing the length of the panels. Like the 10- panel trap, the Dog Bone design exhibits lower stretch

measured on its top panels and side panels. As can be seen in Figure 4.4.21, it also keeps the corners of the tank on the ground even in a 50% overfill state as shown below (4,500 gallons).

Figure 4.4.21 – Dog Bone Trapezoid Design, Corner and End Fill Photographs
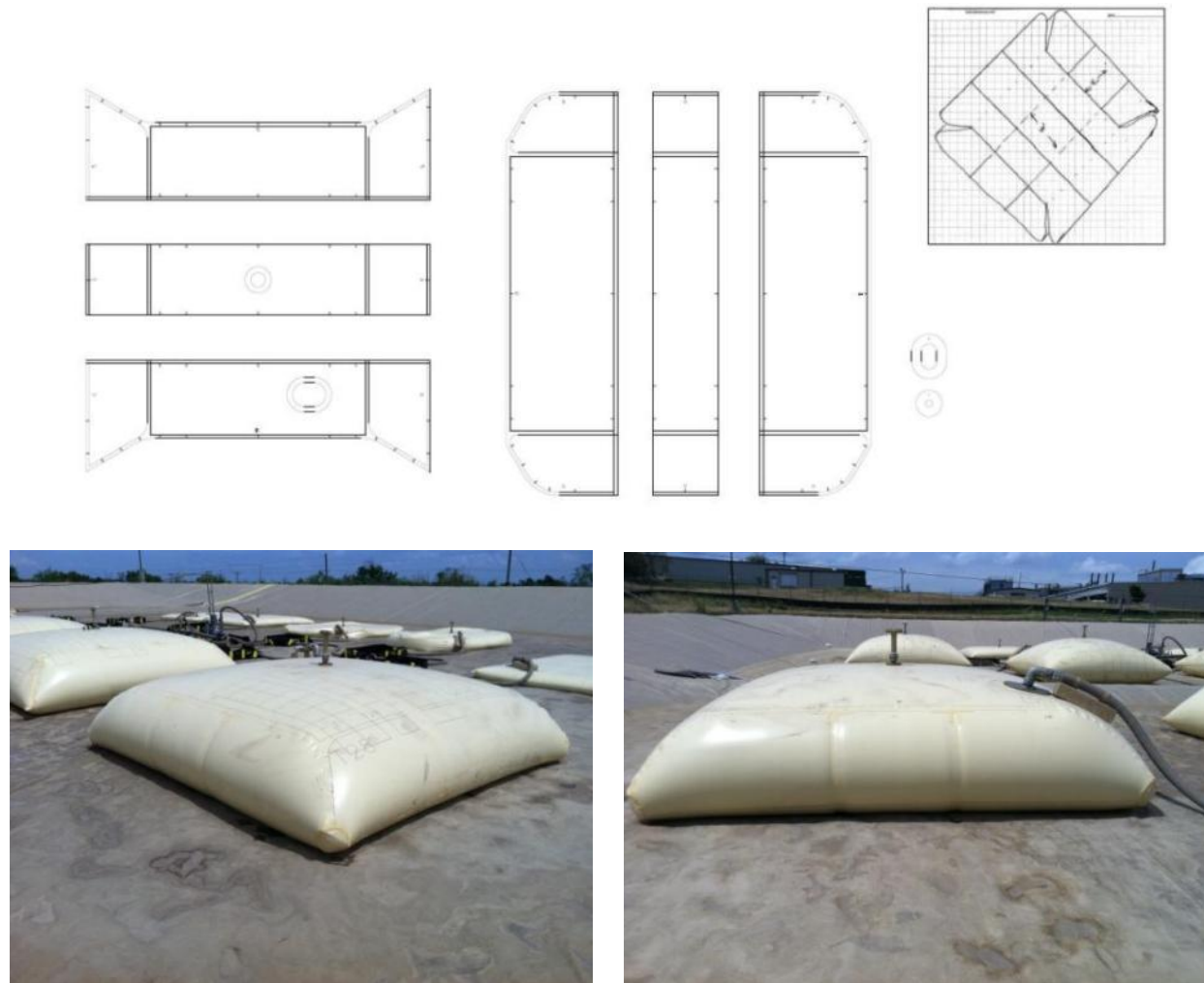
Transverse-T Design (Figure 4.4.22)

The Transverse –T design is a variant to the standard design tank. In this case, an opposing panel on the bottom of the tank is used to close the wraparound sheets that make up the tank body. This leads to a tank design with only 4 "T" seams. It could be further simplified by joining the wraparound ends with a double butt seam, thereby creating only 2 "T' seams. Since its geometry is so close to the 'standard' standard design tank in design, similar performance inadequacies in Transverse-T Design may occur.

Figure 4.4.22 – Trans-T Design, Corner and End Fill Photographs
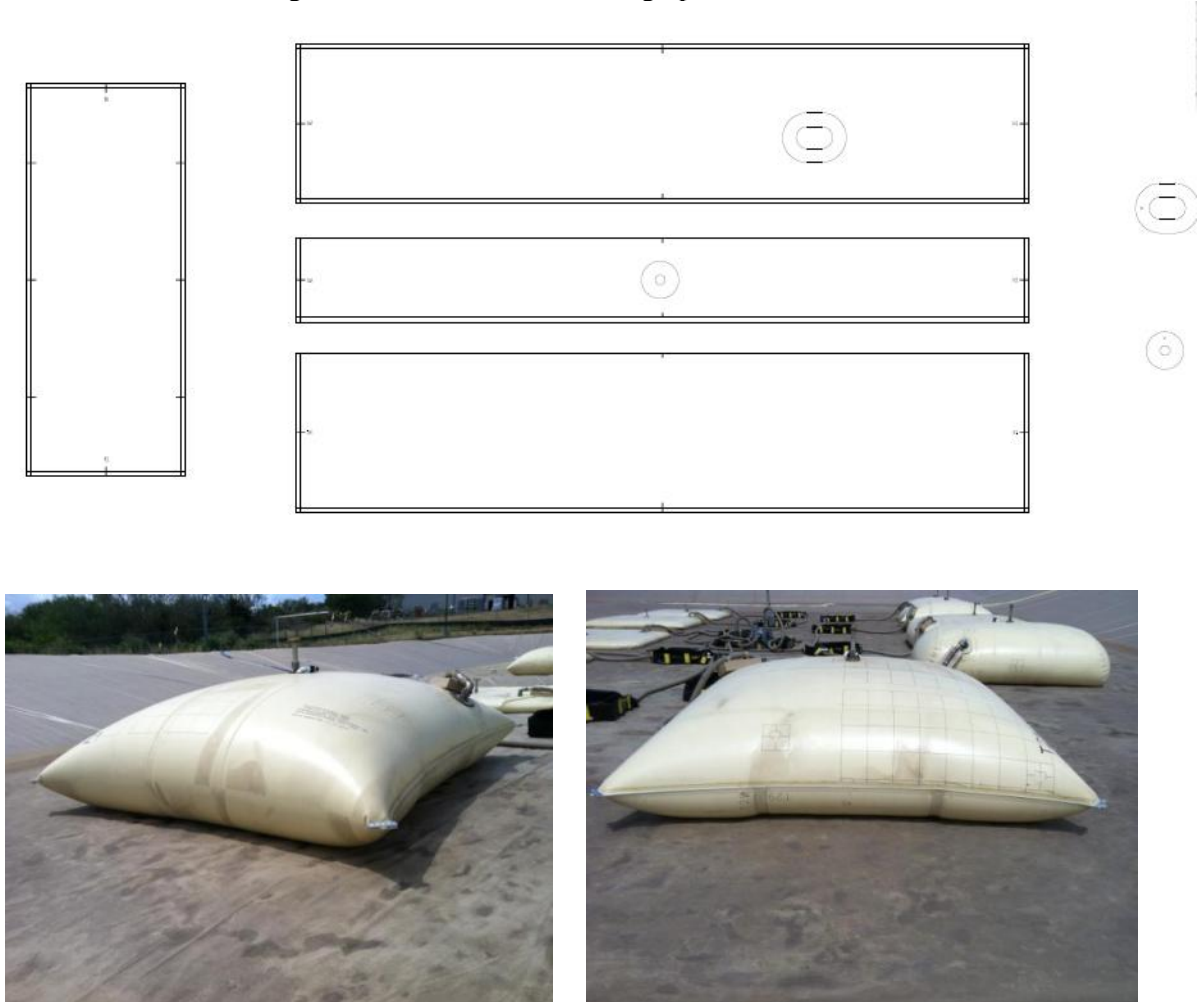
4.5   Field Test Tank Fabrication

4.5.1   Material Lot Selection

A single lot of Seaman, 1940 PTFF MS337 fabric was dedicated for seam sample fabrication using the various weld methods. The run number was 100678; roll tag #'s 12 – 21. The lot was characterized and tested to ensure consistency. A single lot was chosen for the work to minimize the impact that fabric variability might have on field tank performance evaluation. The test data on the initial lot is shown Table 4.5.1 below:

Table 4.5.1 – 1940 Material Lots Used for Tank, Dead Load and Leak Test Rig Testing

Yards	Run Number	Tag Number	Hot Air Weld Adhesion	Dielectric Weld Adhesion
201	100678	1100678020		
206	100678	1100678021		
192	100678	1100678019		
200	100678	1100678018		
200	100678	1100678017		
145	100678	1100678016	≥ 50 lbs$_f$/in	≥ 50 lbs$_f$/in
200	100678	1100678015		
200	100678	1100678014		
200	100678	1100678013		
200	100678	1100678012		

4.5.2   Welding

Industry CFT fabricators, with a familiarity with multiple welding methods, were contacted and invited to participate in this program. Two fabricators committed and were enlisted to provide the tanks for the field and laboratory studies. Both fabricators were provided a copy of the FY2008 program report (Contract No. SP0600-04-D-5442, Delivery Order 1017) including the specific Process (Section 6.0) and Quality Control (Section 7.0) recommendations related to optimal panel welding. Per the conclusions in the report, a 55 lbs$_f$/in. initial panel weld seam adhesion was considered to be the target.

For some of the field study tank designs, the fabricator utilized both Hot Air Welding (HAW) and Radio Frequency (RF) welding. Typically, HAW welding was utilized for creating the panel seams while RF welding was the predominant choice for closing seams due to the need to join and seal more than 2 ply of material. RF was also preferred for the double butt seam welds, again where more than 2 ply (3 ply in this case) needed to be joined.

Hot Air Welding

For hot air welding, the FY2008 report recommendations are listed in Table 4.5.2.

Table 4.5.2 – Recommended Hot Air Welding Conditions

Machine/Device/Tool	Characteristics		Methods					Reaction Plan
	Product	Process	Product or Process	Evaluation Method	Sample Size	Sample	Control Method	
		Speed, ft/min	4 to 4.5	Machine display	1	1 x/ shift	Control Sheet	Manual adjustment
		Pressure, psi	80	Machine display	1	1 x/shift	Control Sheet	Manual adjustment
		Air Temp, F	850	Machine display	1	1 x/shift	Control Sheet	Manual adjustment
Hot Air Welder 2" 100A wheel 1-7/8" tip 2" Guider		Nozzle position, inches	0.5	Machine display	1	1 x/shift	Control Sheet	Manual adjustment
		Delay	3	Trial	1	1 x/shift	Control Sheet	Manual adjustment
	Weld Width		2" min	Ruler	1	each panel	X bar - R chart	Check/correct markings
	Weld Adhesion		55 lbs/inch min	ASTM D751	test weld	2 x/ shift	X bar - R chart	Run Hold - notify QC
	Weld consistency		clean to base	Visual	test weld	2 x/ shift	Visual to std	Run Hold. Check tip position, check weld wheels for damage of buildup, run test weld
	Weld Aesthetics		no defect	Visual	1	each panel	Visual to std	Check weld wheels for damage, Maintenance

The top blanket for Tank 25 is shown in Figure 4.5.2. The three panels were Hot Air Welded (HAW) together on a Miller Weldmaster T-500-2 with a swing arm, one at a time, with the prototype profile tape along the warp direction (Figure 4.5.1). When welding this tank, the top and bottom blankets (three panel sections) were welded separately and then each joined to the continuous "belly band". This proved to be a material handling challenge (taking seven personnel 45 minutes). Figure 4.5.2 shows a close up of the profile tape ends extending out on both the inside and outside from the original top blanket. The fabricator felt that if the durometer of the polyurethane was lowered, the profile tape would flow better and actually work quite well (Figure 4.5.2).

Figure 4.5.1 – Belly Band (Tank 25) Top Blanket Welded

Figure 4.5.2 – Top Blanket Weld Showing Profile Tape "Pucker"

The design radius for Tank 25 (Figure 4.4.18) was the radius of 24 inches recommended during the original design reviews. After working with the design the fabricator felt that an even more generous radius on any curve would be more forgiving and tend to pucker less (Figure 4.5.3).

Figure 4.5.3 – Belly Band 24-inch Corner Radius "Pucker"

If the feed rates vary between the belly band weld to the top versus the bottom blanket, a counter twist between tank top and bottom could be introduced which may potentially cause the tank to be unstable when filled with fluid. The fabricator who welded this tank has experience with a similar design of their own and cannot see it being done practically in any size larger than 3,000 gallons. The twist is much more predominant if the top and bottom are started in opposite directions. When the tank is flipped over and set-up for the easiest feed through the welder it aligns the material in the opposite direction from the initial weld. The picture below illustrates that even though the initial match marks were aligned, by the time the band came to a close the match marks were off by > 6 inches (Figure 4.5.6). It appears that this difference increases when the fill direction on the belly band panel opposes the warp direction on the top and / or bottom blankets.

Figure 4.5.6 – Belly Band Offset Match Marks

For any shapes involving welding complex curves or radii, match marks were increased to 6" increments per the recommendation of a fabricator. This was necessary for the fabrication of the more complex Tank 27 (Quonset hut) design (Figure 4.5.7).

Figure 4.5.7 – Complex Radius on Quonset Hut which Requires Additional Match Marks
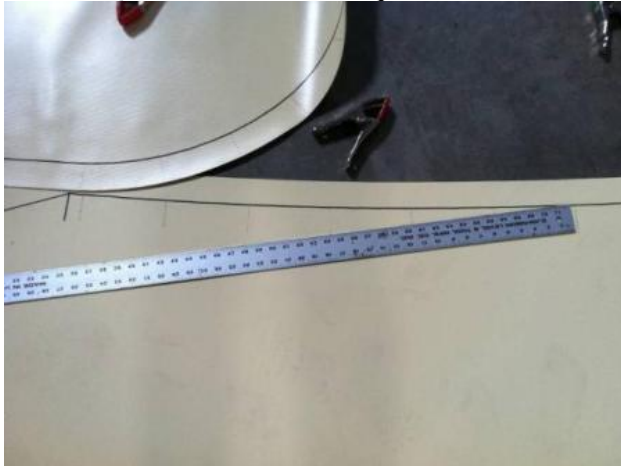
An additional issue is the application of tape on the inside of the tank once the closing seam has been completed. Since the tank has been closed, the fabricator must have personnel climb inside of the manway to complete taping on the inside. This has proven to be problematic since it involves keeping the tank propped open; personnel working in a confined space; the required use of a hand welder; is more prone to human error, and may create new leaks by hot air gun nicks or misses. Any unintended damage to the inside of the tank due to the hand held hot air welder then needs to be patched or sealed. If the inside seam involves a curved surface, it makes it even harder to do.

To remediate this inside panel capping issue, the fabricators have both created solutions involving the use of a sealing compound. In one case, a proprietary adhesive coat is applied. In the other, a polyurethane compound is extruded onto the seam (Figure 4.5.8). The extruded compound has also been used on the outside of the tank to reinforce areas such as circular corner patches and "T" seams.

Figure 4.5.8 – Extrusion of Polyurethane Compound onto Corner of Tank 28

One unique approach discovered during the fabrication process was the cap-stripping of the end a curved panel with the 1" coated fabric prototype tape (See Figures 4.5.9 to 4.5.11). This was employed on the fabrication of Tank 24 (Canoe Ends design – Figure 4.4.17). First, the curved panel ends were cap-stripped with the 1" tape folded in half (~ ½" inside and outside – Figure 4.5.9). Then the remaining width of the 2" wide seam was HAW welded against the mating panel (Figure 4.5.10). There was also a

bit of a material-handling logistics issue. It took six personnel to weld the two canoe profiles together for each end with a Miller Weldmaster T-500.

Figure 4.5.9 – Cap-Stripped End of Curved Panel   Figure 4.5.10 – 2" Weld Completion
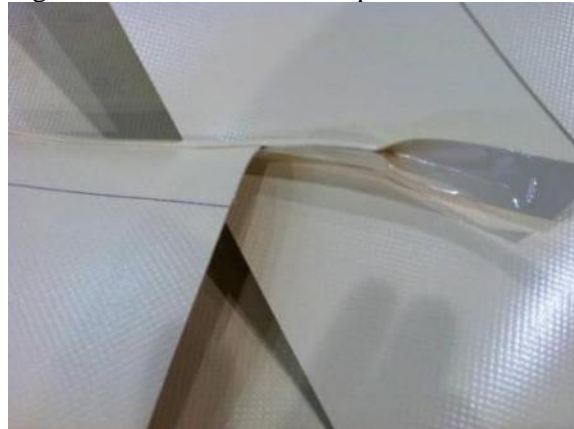
However, upon completion, this approach yielded a smooth curved edge without any puckering (Figure 4.5.11).

Figure 4.5.11 – Completed Welded Radius without Puckering

During the initial attempt to weld Tank 28 (Dog Bone Trapezoid – Figure 4.4.21), the top and bottom three- panel sections were welded first and then a closing seam was applied to the periphery of the tank. This proved to be a logistics material-handling challenge. After some brainstorming, an alternative approach was tried. The three bottom panels were first welded together. Two of the top three panels were then welded together and their outside edges were welded to the bottom blanket on both ends. Finally, the top was closed across the final open warp panel seam.

Two different types of welding heads were utilized for the Radio Frequency welding (Table 4.5.3). A standard flat plate platen was used for the double butt seams and some closing seams by one fabricator. The other utilized a "Slinky Bar" welding head supplied by Seaman Corporation. The slinky bar head is shown below separately and in use on the welder on a tank closing seam. As the name suggests the 13" x 2" head of the slinky bar is made of a series of ⅛" wide plates stacked side-to-side across the long axis of the bar. This allows the slinky bar to adjust height automatically when stepping up or down across

multiple plies of material. Hence, it is a logical choice for tough-to-weld areas like closing seams and corners.

Table 4.5.3 – Radio Frequency Welding

Machine/Device/ Tool	Characteristics		Methods					Reaction Plan
	Product	Process	Product or Process	Evaluation Method	Sample Size	Sample Frequency		Control Method	
RF, 2 x 33		Seal time, seconds	6, +1/-0.5	Machine display	1	1 x/ shift	1 x/ shift	Control Sheet	Manual adjustment
		Pressure, bar	4.5	Machine display	1	1 x/shift	1 x/shift	Control Sheet	Manual adjustment
		Amps	1.63 to 1.95	Machine display	1	1 x/shift	1 x/shift	Control Sheet	Manual adjustment
		Preseal time, seconds	3	Machine display	1	1 x/shift	1 x/shift	Control Sheet	Manual adjustment
		Cooling time, seconds	15	Trial	1	1 x/shift	1 x/shift	X bar - R chart	Manual adjustment
		Air Coolant temp, F	80 F	Machine display	1	1 x/shift	1 x/shift	Control Sheet	Manual adjustment
		Overall cycle time, seconds	24 to 28	Machine log	1	1 x/shift	1 x/shift	X bar - R chart	Maintenance
	Weld Width		2" min	Ruler	1	each panel	each panel	X bar - R chart	Check/correct markings
	Weld Adhesion		55 lbs/inch min	ASTM D751	test weld	2 x/ shift	2 x/ shift	X bar - R chart	Run Hold - notify QC
	Weld consistency		clean to base	Visual	test weld	2 x/ shift	2 x/ shift	Visual to std	Run Hold. Check platen alignment, check tool, run test weld
	Weld Aesthetics		no defect	Visual	1	each panel	each panel	Visual to std	Check contact surfaces for damage, Maintenance

Figure 4.5.12 – Slinky Bar

Figure 4.5.13 – Slinky Bar in Use on Dielectric Welder Over Closing Seam

The welded corner with clamp design was carried over from the FY2008 program Model Tank in an effort to maintain a baseline for comparison. Both fabricators determined that this design introduced a number of potential leak sources they normally do not encounter. Both the closing seam and the corners of the FY2008 design tanks require the welding of multiple plies of material (>2). Figures 4.5.14 and 4.5.15 show a typical welded, unclamped corner (Figure 4.5.14) and a corner that was film taped to seal off the end and prevent leaking (Figure 4.5.15).

Figure 4.5.14 – Typical Welded Unclamped Corner   Figure 4.5.15 – Corner with Additional Film
with Clamp Holes

When bolts were added to the corner, care needed to be taken to make sure they were not over-torqued. If this occurred, as in Figure 4.5.16), it would cause the clamp plates to cantilever (narrower on outside clamp gap, wider in the middle) and create bridging and an open pathway over the two middle bolts.

Figure 4.5.16 – Clamp Plates Cantilevered –   Figure 4.5.17 – Associated Corner Leak
narrower gap on outside between plates

A few additional issues were captured during the RF welding process. If welding multiple plies does not appear to create an integral weld at the appropriate power setting, increasing the platen pressure or weld power should be the first options tried. In some instances, a closing seam weld was hit multiple times to get an integral weld. However, too much compound flow may occur leaving either a damaged fiber bundle at the seam or exposed scrim (Figure 4.5.18).

Figure 4.5.18 – Exposed Fiber Bundle Due to Compound Overflow

4.5.3   Qualification Testing

After fabrication, all tanks were subjected to the MIL-PRF-32233 specification qualification testing. To check for leaks, initial air and water fill tests were performed. In addition, a strapping chart was developed through maximum fill volume or 150% fill.

4.5.3.1 Air Leak / Bubble Testing

Air testing revealed a number of potential issues that needed to be addressed (Figure 4.5.19). Included were gaps in seam tape (Figure 4.5.20) as well as areas where multiple RF hits overcooked the material (Figure 4.5.21).

Figure 4.5.19 – Air Testing   Figure 4.5.20 – Seam Tape Gap

Figure 4.5.21 – Bubble Formation from Over-Cooked RF Weld

There were two differing approaches to this test, both of which met the requirement as stated. In one case, the air supply was shut off once pressurized above the target set point of ½ psig. As long as the pressure held, the tank was then checked for leaks with soapy water. In the other case, a continuous supply of air pressure (>½ psig) was left on with a trickle bleed-off controlled with a separate valve that was minimal compared to the air volume supplied. The valve was adjusted to maintain a constant maximum pressure of ½ psig while providing steady, low volume airflow to the tank. In this case, with air allowed to flow, it appeared to offer a more robust test and detect very subtle leaks when compared to the target set point of >½ psig.

4.5.3.2 – Water Fill Testing

All 20 tanks were filled at increments of 500 gallons or more, initially to 3,000 gallons. In addition, they were then filled to either their fill maximum (water discharging out of the vent) or 150% fill. The heights were measured during these fills to create a unique strapping chart for each tank. Figure 4.5.22 shows a FY2008 model tank in a maximum overfill state (~4,000 gallons).

Figure 4.5.22 – FY2008 Model Tank Over-Filled to 4,000 gallons

After overfilling was completed, the tanks were allowed to sit for at least 24 hours and checked again for leaks. Figure 4.5.23 illustrates leaking bolts on a manway / filler / discharge port cover plate. These bolts were re-torqued and verified to ensure that they were to specification and the problem was resolved.

Figure 4.5.23 – Manway / Filler / Discharge Bolt Leaks

In some cases, leaks not detected during the air test were picked up through the overfill water test. Figure 4.5.24 depicts a leak most likely caused by the heat from a hand-held hot air gun or extruder used to add a polyurethane sealant to an internal weld seam.

Figure 4.5.24 – Flaw in Panel Created by Internal Hot Air Gun Miss at Corner

Leaks like those shown in Figure 4.5.24 were patched and retested. The fabricators' approaches differed in the ways they sealed leaks that surfaced during air and water testing. In some instances, if the leak was over a larger area (example >1"), a patch was cut and welded and/or glued into place. In other instances, where the breach was not as significant, either an adhesive or polyurethane extrudite or sealant was used to seal the flaw. A complete discussion of all leaks observed and detailed during the post field testing tank forensics effort is detailed in Section 5.4.6.5.

Upon completion of the water fill tests, all tanks were drained, dried and packed for transit to either SwRI or Seaman Corporation.

5.0   Field Testing

5.1   Site Selection

After careful review of multiple military, government and commercial sites, Southwest Research Institute (SwRI) was selected as the preferred test site. SwRI was selected based on cost, ease of logistics, a site easily adaptable for the needs of this test, flexibility in testing and overall experience and comfort with working with JP-8.

SwRI had an unused 200 ft x 200 ft area (Figure 5.1.1) that was determined as optimal for this testing. It was an on-site, controlled, fenced-in area with a previously excavated berm (Figure 5.1.2). Logistically, it was part of a major R&D facility with ample resources and personal for support. All of the necessary utilities and provisions were within reach. SwRI's location on the San Antonio 410 Loop made it easy to access and for shipping materials.

Figure 5.1.1 – SwRI Available Berm Area

Figure 5.1.2 – Secure Fenced in Berm Area

5.2   Site Design and Layout

Based on the bermed area size, it was determined that it would be possible to operate up to twenty 3,000
gallon tanks. This left room for a 50,000 gallon tank that would be used to verify stretch at 100% fill-
volume as well as a reserve safety tank. An initial layout plan (Figure 5.2.1) was created for review and
discussion by DLA, Seaman Corporation and Southwest Research Institute. Once approved, it served as
the basis for the formal berm area excavation design authorized by SwRI facilities planning (Figure
5.2.2).

Figure 5.2.1 – Schematic for Site / Berm Layout
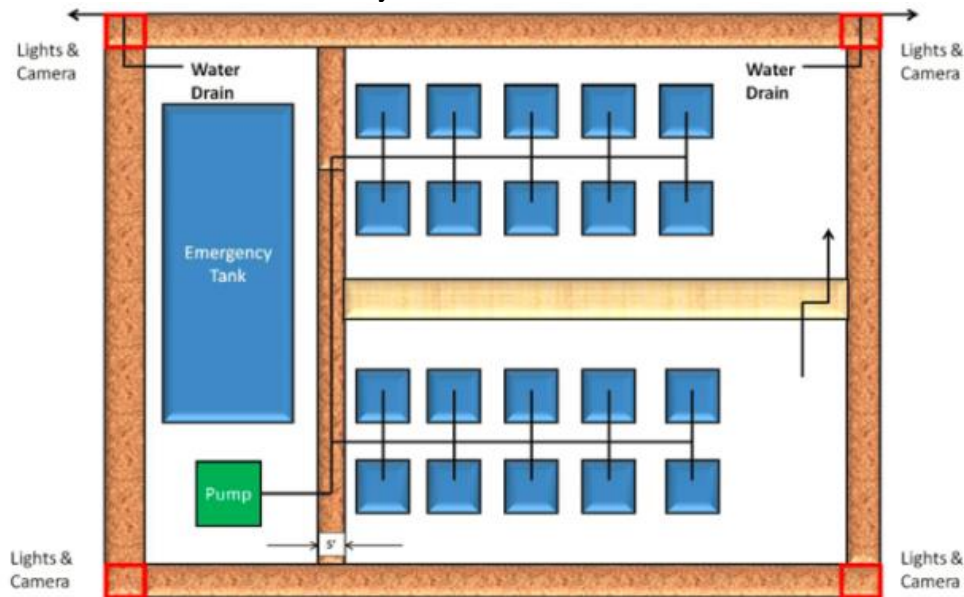
Figure 5.2.2 – SwRI Facilities Plan
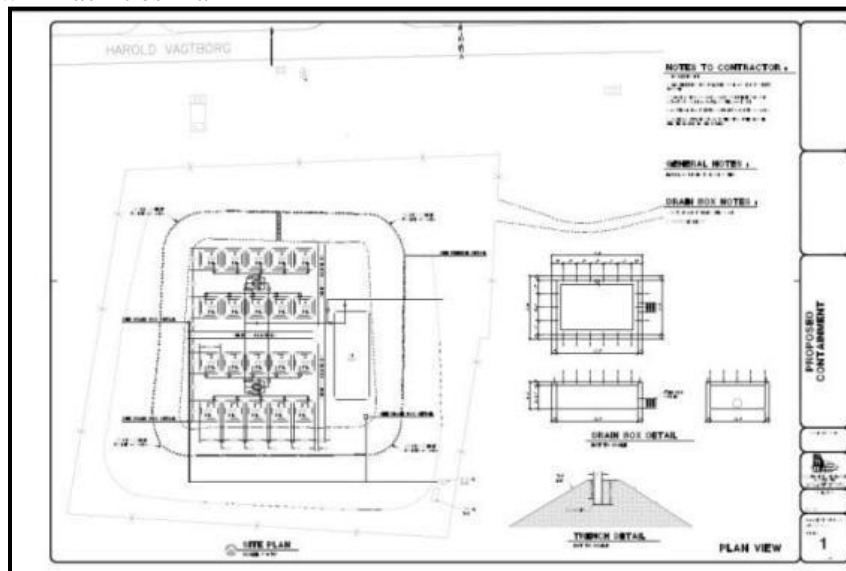
The remaining details of the install are discussed in Appendix H.

5.2.1   Tank Layout

After multiple iterations, the tank layout was finalized (Figure 5.2.3). The fabricators designs were numbered as Tanks 10-15, the FY2008 design variants as Tanks 16-23 and the unique prototype designs as Tanks 24-29. Since there was no performance history relative to the unique prototypes, it was decided to locate them closest to the drainage at the lowest grade in the berm. The two 3,000 gallon tank sections (10 tanks each) were designated as the Teen (Tanks 10 – 19) and Twenty (Tanks 20 – 29) berms for documentation and communication purposes (Figures 5.2.3 and 5.2.4).

Figure 5.2.3 – Schematic Showing Teen Berm (bottom) and Twenty Berm (top)

Figure 5.2.4 – Teen / Twenty Berm Bays from Tank 11 Corner

5.2.2   Plumbing Layout and Shuttling

5.2.2.1 Tank / Flow Network

5.2.2.1.1 Pump

The Gorman Rupp Roto-Prime® Pump was recommended and selected based on a review of the tank farm plumbing layout, network modeling and design plan for fuel shuttling, overall system filling and emptying. The plumbing and hose line layout for the tank farm involved hose runs that are typically longer than might be seen in a standard CFT installation. This model of pump has be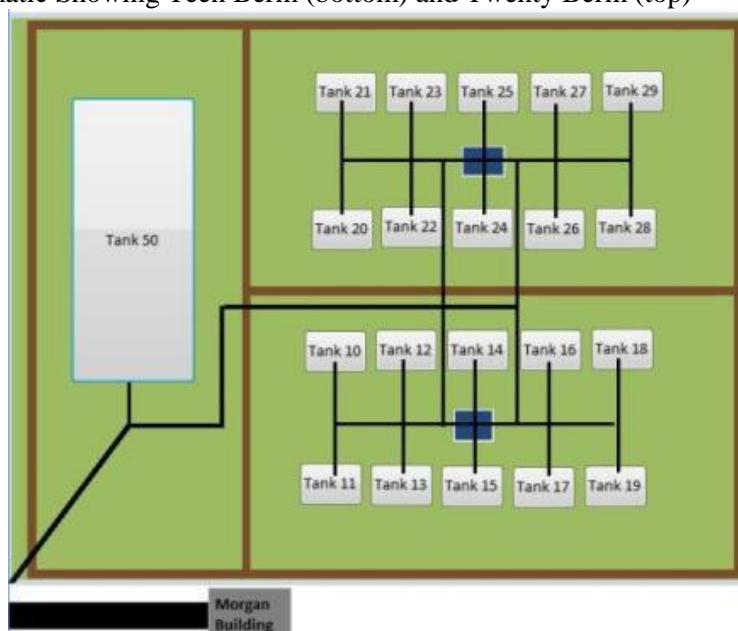en used successfully for years by the USAF in a fuel-powered version. The electric version was selected for repeatability and to keep operating costs down. A total of three pumps were purchased for the testing; one for each of the two 3,000-gallon tank shuttle bays and one as an emergency back-up. The Gorman Rupp Roto-Prime® pumps ability to evacuate air from the lines and, if necessary, from the fuel tanks, paired with the extensive hose runs for the shuttling network, made them the preferred choice for this application.

The pump stand was plumbed in a manner to allow for flow from odd to even tanks and between the Teen and Twenty tank bays and the 50K safety tank, just by opening or closing the appropriate valves on the stand (Figure 5.2.5). On the back of the pump stand is the flow tube access for making flow measurements (Figure 5.2.6).

Figure 5.2.5   Front of Pump Stand with Shuttling Valve Access

Figure 5.2.6 Back of Stand Showing Pump Discharge and Flow Tube

5.2.2.1.2   Tank Farm Flow Network Optimization with MacroFlow CFD

During an early review of the SwRI Tank Farm layout, a number of concerns were raised by DLA's military subject matter experts (SMEs) regarding fuel shuttling and excessive pump cavitation. This was due mostly to their personal field experience with similar networks. Pump cavitation is a critical issue that could have adversely affected the test and shuttling schedule as well as caused pump damage. In an effort to minimize pump cavitation and optimize fuel transfer and shuttling, the entire network was modeled with the use of MacroFlow. Previous experience with this program had led to the successful design of many complex compressible and incompressible fluid networks. It allows for complete flow network system design, simulation and analysis on the computer, saving time and cost of multiple physical system iterations. Through its use across multiple networks, it has led to computer- modeled solutions that are typically within 10% of the actual physical system.

A CFT Tank Farm design layout was created by Seaman Corporation and presented to SwRI for review and approval by their Facilities, Environmental and Safety teams. This became the basis for the approved scaled Containment Plan from SwRI. The MacroFlow program was used to optimize this layout ahead of time, with tank locations, pump curves, network line lengths and sizes, valves, pump curves, JP-8 fluid properties and typical environmental extremes included. A series of different models were run to verify normal (shuttling) between pairs of tanks as well as worst-case transfer scenarios. In all cases, the operation of the network was checked at various locations to verify that the minimum equilibrium (or saturated) vapor pressure for the onset of cavitation was not reached.

The MacroFlow model for the SwRI Tank Farm network is shown in Figure 5.2.7.

Figure 5.2.7   SwRI Tank Farm MacroFlow Network Model
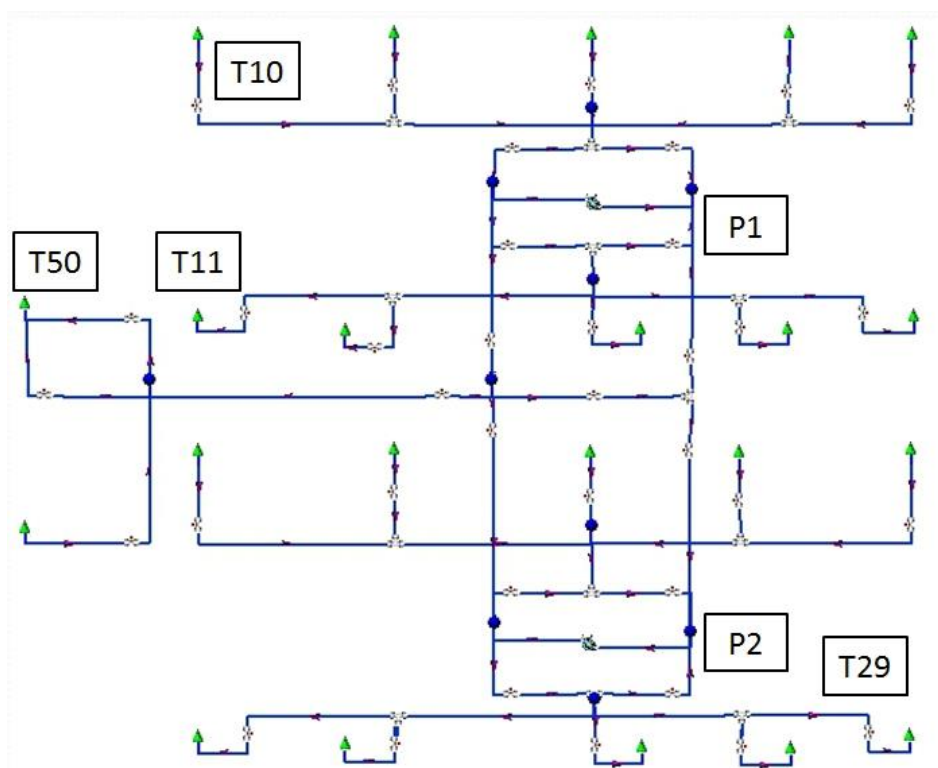
A series of 22 green triangles (boundary nodes) represent the twenty 3,000 gallon test tanks (e.g., T10, T11 and T29), the 50,000 gallon reserve tank (T50) and the fuel tanker (lower left unlabeled). The blue lines represent the hoses used to connect the network. The two pumps are represented by P1 and P2, in the center of the recirculation loop in each tank bay. The 10 blue circles are generic nodes which are used as pressure measurement points. Ball valves are located throughout.

To model the network, three test cases were chosen. The first was a straight pair shuttle from Tank 10 to Tank 11 through Pump 1, most representative of typical operational use. The graph of static pressure throughout the network is in Figure 5.2.8.

Figure 5.2.8   Test Case 1 – Shuttle Pair Tank 10 to Tank 11
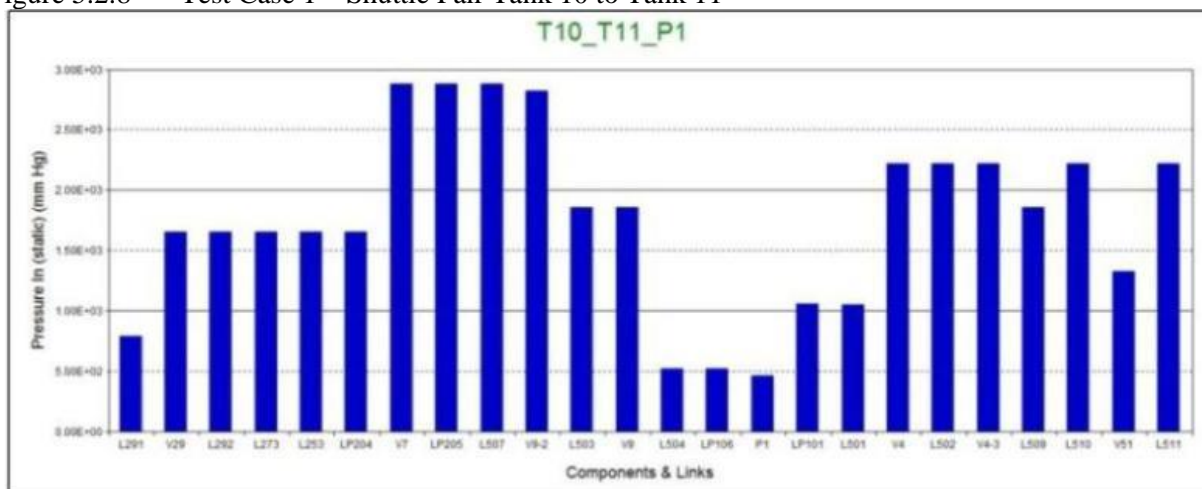
The last two cases were chosen as worst-case scenarios. The second case represents having to shuttle from Tank 10 (in the top bay, upper left corner) to Tank 29 (in the bottom bay, farthest right location). The assumption was that Pump 1 would not be available for use (i.e., theoretically down for repair). The results for this example are shown in Figure 5.2.9.

Figure 5.2.9   Test Case 2 – Shuttle from Tank 10 to Tank 29 through Pump 2
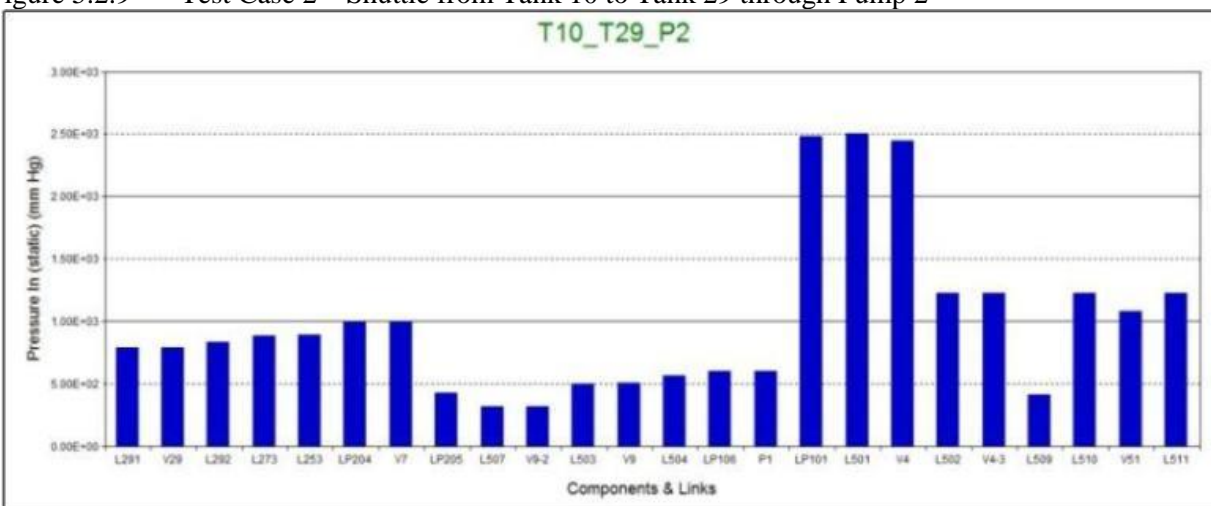
The final model looked at shuttling from Tank 29 back to the T50 reserve tank through P1. Once again, the assumption was that P2 (Pump 2) was not available for use and the fuel needed to be off loaded to the reserve tank. The graph of this situation is shown in Figure 5.2.10.

Figure 5.2.10   Test Case 3 – Draining Tank 29 to Tank 50 through Pump 1
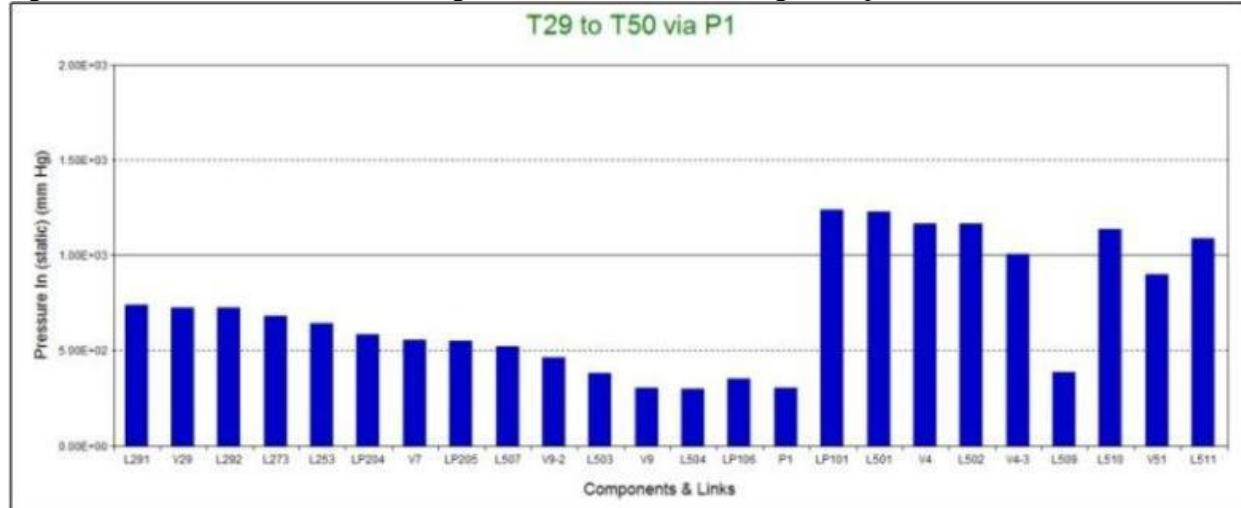
For all three cases, the pressure monitoring throughout the network indicated that, even though the models simulated were worst case, the minimum equilibrium (or saturated) vapor pressure for the onset of cavitation was not reached. All cases were run at an external temperature of 110 °F to ensure that they reflected "worst case" based on environmental conditions.

The modeling was used to finalize the tank layout, fuel shuttling network and pump specification, so that it operated consistently and repeatedly; regardless of changing environmental conditions. The flow network worked correctly from test onset through completion, without any cavitation or need to re-plumb the system.

5.2.2.2 Tank Shuttle / Measurement Schedule

The tanks were laid out in even/odd-numbered pairs for shuttling and overall data management. In addition, they were split into two berms (10 tanks in each berm):1) for better control over a potential catastrophic leak situation, and 2) to have two independent pumps available in case one pump or berm was inoperable or out of service. Figures 5.2.11 and 5.2.12 show the location of the tank pairs, with Tanks 10-19 in the Teen Bay and Tanks 20-29 in the Twenty Bay. The 50,000 gallon reserve tank was located in its own bay due to its large size and volume and the need for access to the tanker truck.

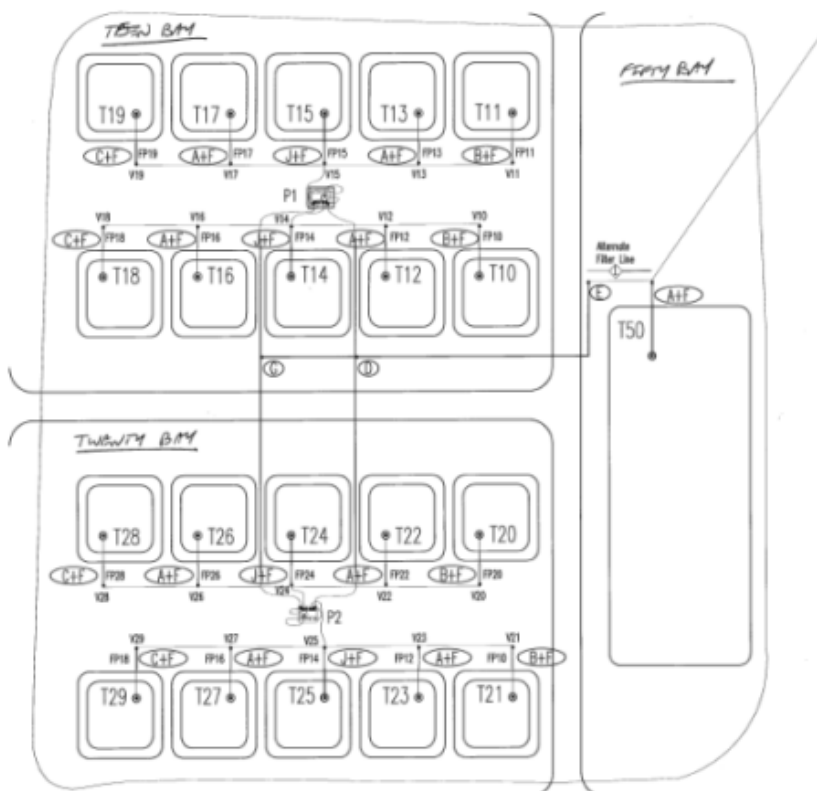Figure 5.2.11   Tank Pair Location Schematic

Figure 5.2.12   View of Tank Layout from Tank 29 Corner

For ease of measurement management and recording, it was decided to stagger overfill of the even and odd numbered tanks on a weekly basis. For example, for a given week, all of the even tanks would be overfilled on Day 1. The tanks were allowed to settle for 24 hours prior to the stretch measurements being performed. The remaining days of the week, the panel stretch and IR camera measurements would be made on the tank. The process would then be reversed the following week with the odd number tanks being overfilled and measured. The under-filled tank in each pair would contain the remaining fuel which was typically ⅓ - ½ the volume of a 3,000 gallon tank.

Each tank had a standard panel stretch measurement grid pattern applied during panel plotting and cutting. In addition, a grid which covered a full quarter of the tank was added to verify whether any other location presented higher stretch. The seven predetermined panel locations were lettered from A – G. Each panel was plotted out exactly in a 10-inch by 10- inch perfect square, translated directly from the AutoCAD design. Since the pen line was ¼ inch wide and stretch measurements were made on the inside of the panel square, the initial baseline width was 9-7/8 inches. Arrows were added at both the warp and fill centers of each square to aid in measurement. The warp arrows shown run in the vertical direction of each letter while the fill arrows run horizontally. An example of the top of a tank illustrating a typical gridding pattern is shown in Figure 5.2.13.

Figure 5.2.13   Tank Gridding Layout with Typical Panel Locations
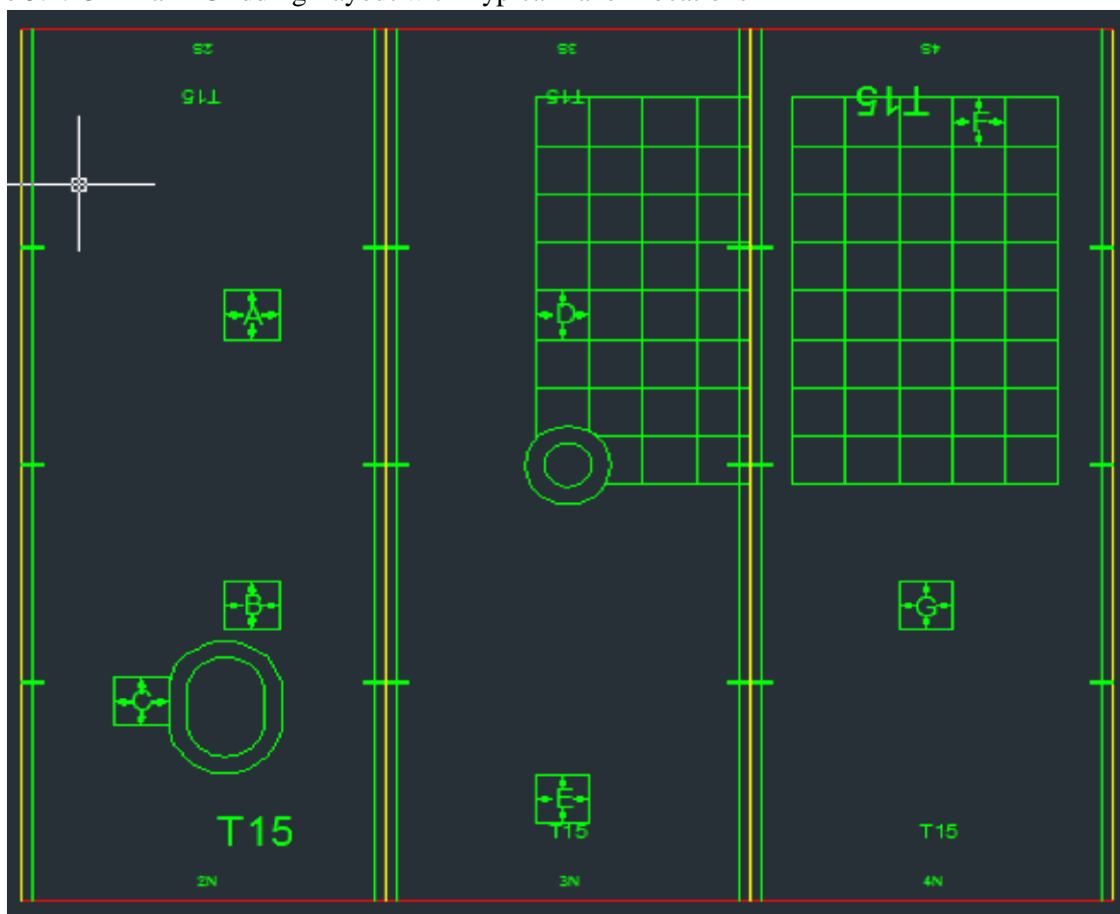
Based on this information, a panel measurement schedule was created (Table 5.2.1). This schedule was followed to maintain consistency in measurement (i.e., adequate measurements of all panels available), especially when measurement or shuttling was interrupted by inclement weather or other circumstances.

Table 5.2.1   Panel Stretch Measurement Schedule

| Number of Measureable Panels	Panels Measured	Panels NOT Measured	Tank	Measurement Day			
				1	2	3	4
EVENS							
5	A, B, E, F ,G	C-D	T10	A-B	E-F	G-A	G-E
7	A, B, C, D, E, F, G	---	T12	A-B	C-D	E-F	G-D
6	A, B, D, E, F, G	C	T14	A-B	D-E	F-G	G-D
7	A, B, C, D, E, F, G	---	T16	A-B	C-D	E-F	G-D
7	A, B, C, D, E, F, G	---	T18	A-B	C-D	E-F	G-D
6	A, B, D, E, F, G	C	T20	A-B	D-E	F-G	G-D
6	A, B, D, E, F, G	C	T22	A-B	D-E	F-G	G-D
6	A, B, D, E, F, G	C	T24	A-B	D-E	F-G	G-D
6	A, B, D, E, F, G	C	T26	A-B	D-E	F-G	G-D
7	A, B, C, D, E, F, G	---	T28	A-B	C-D	E-F	G-D
ODDS							
5	A, B, E, F ,G	C-D	T11	A-B	E-F	G-A	G-E
7	A, B, C, D, E, F, G	---	T13	A-B	C-D	E-F	G-D
6	A, B, D, E, F, G	C	T15	A-B	D-E	F-G	G-D
6	A, B, D, E, F, G	C	T17	A-B	D-E	F-G	G-D
7	A, B, C, D, E, F, G	---	T19	A-B	C-D	E-F	G-D
6	A, B, D, E, F, G	C	T21	A-B	D-E	F-G	G-D
6	A, B, D, E, F, G	C	T23	A-B	D-E	F-G	G-D
5	A, B, D, E, G	C-F	T25	A-B	D-E	G-A	G-D
6	A, B, D, E, F, G	C	T27	A-B	D-E	F-G	G-D
6	A, B, D, E, F, G	C	T29	A-B	D-E	F-G	G-D

5.3 Experimental Design

5.3.1 Overfill Approach

5.3.1.1 Method Defined in FY2008 Program

During the FY2008 effort, it was determined that the stresses seen in a 50,000 or 210,000 gallon tank could be modeled by overfilling a 3,000 gallon tank by up to 150% of its target volume. This assumption was based on stresses derived in larger tanks based on Finite Element Analysis (FEA) and verified in laboratory stretch measurement of an over-filled 3,000 gallon tank (Contract No. SP0600-04-D-5442, Delivery Order 1017, Section 8.0). In this effort, the conclusion was reached that a High Temperature Fuel (HTF) adhesion of 45 lbs$_f$/in would correlate linearly to an initial weld adhesion of 55 lbs$_f$/in (Figure 5.3.1). Based on these findings, a 55 lbs$_f$/in. initial seam adhesion was defined as the target value for an integral panel weld.

Figure 5.3.1   Initial – High Temperature Fuel Weld Adhesion Correlation
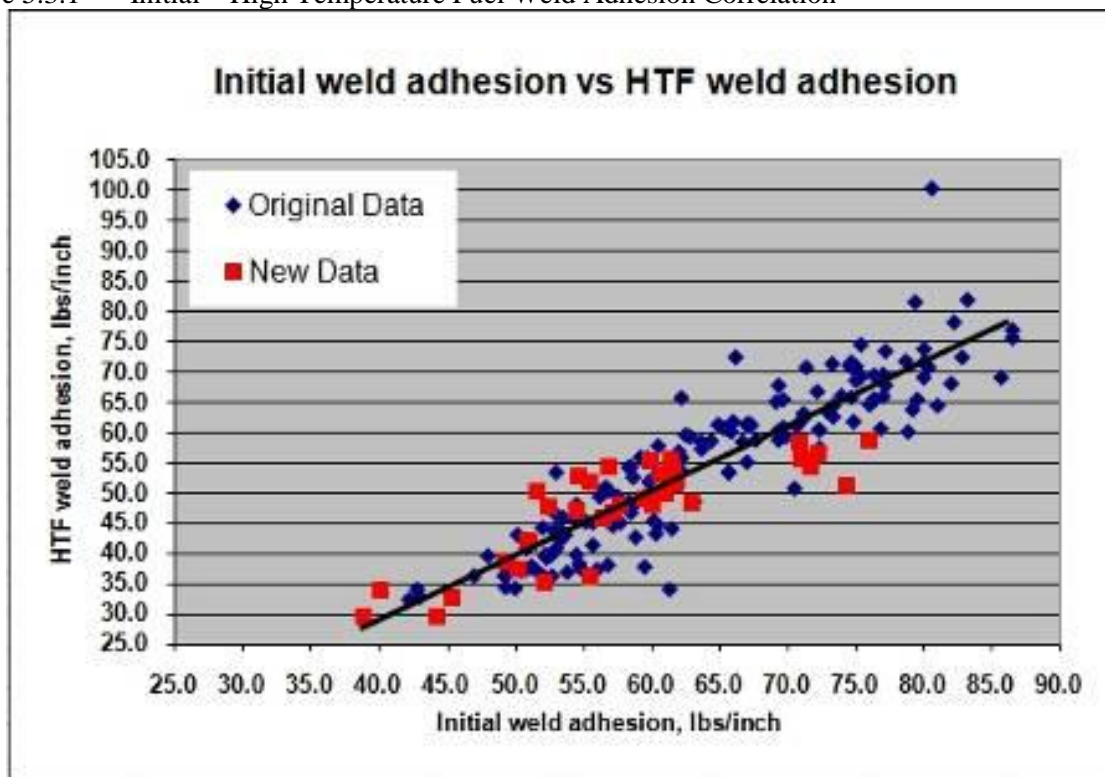
Further, the actual material stretch in both the warp and the fill directions were correlated to load through the 1940 PTFF Biaxial Stretch curve (Figure 5.3.2).

Figure 5.3.2   1940 PTFF Material Biaxial Stretch Curve
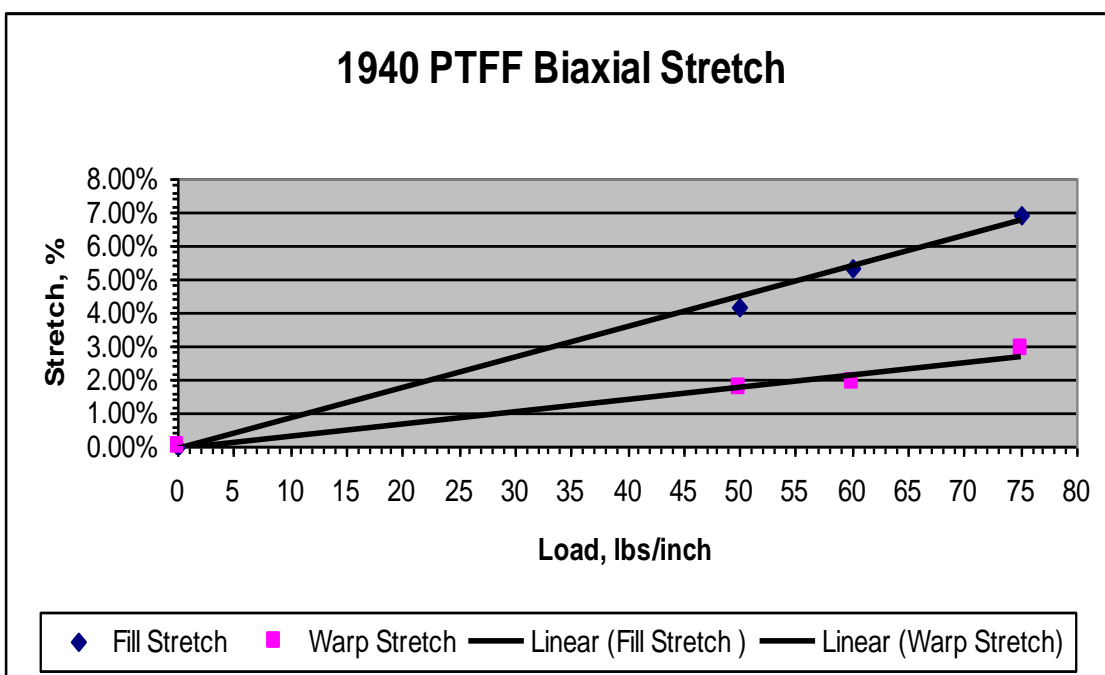
Per this graph, for the 1940 PTFF at a load of 55 lbs$_f$/in, the associated stretch would be ~2% for the warp and ~5% for the fill. It is important to note that during the FY2008 Model Tank testing, multiple stretch panel locations were measured on the tank. The peak value for all of the panel measurements was chosen as representative for both warp and fill stretch for the each fill volume measured, since this would correlate directly to the maximum value of welded seam load that would be recommended.

5.3.1.2 50K 100% Fill Stretch Confirmation

To verify by physical measurement that the 3K tank overfill stretch assumption was correct, the 50,000 gallon reserve tank at SwRI was checked prior to test program onset. The 50K tank was filled to 100% and allowed to settle and equilibrate in the Jun 2012 heat for 3 days, before stretch measurements were made (Figure 5.3.3). The volume of fuel put into the tank (50,000 gallons) was measured on the calibrated flow totalizer meter on the SwRI's tanker truck (Figures 5.3.4 – 5.3.5).

Figure 5.3.3   Tank Filled to 100% Volume – 50,000 Gallons

Figure 5.3.4   SwRI Tanker Truck   Figure 5.3.5   Truck Calibrated Flow Totalizer

After a three-day settle and equilibration period, both warp and fill panel measurements were made on the 50K tank. Percent stretches for the six measured panels for both warp and fill are graphed in Figure 5.3.6. Panel C was not available for measurement due to a manway / filler discharge flap that interfered with the measurement.

Figure 5.3.6   Warp and Fill Stretch Verification on 50,000 Gallon Tank
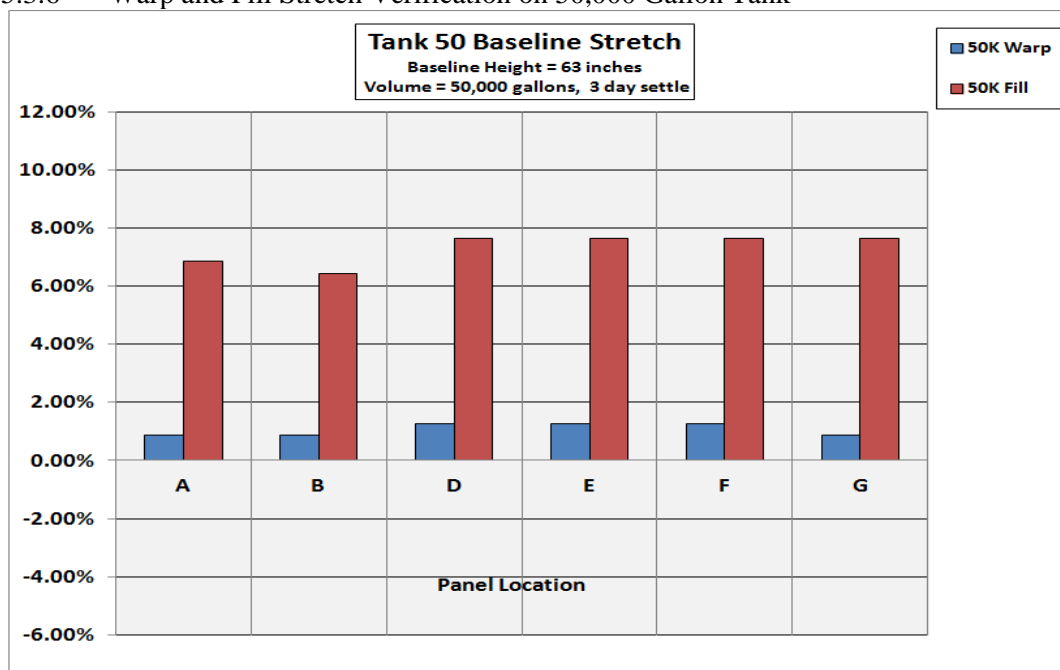
The peak warp stretch is ~1.5% while the peak fill is ~7.5%. Hence, a target peak warp stretch of 1.5% or a peak fill stretch of 8% at overfill in a 3,000 gallon tank should correlate well to the loads seen in a 50,000 or 210,000 gallon tank.

5.3.2   Fuel Specification and Monitoring

To understand the impact of fuel storage on the CFTs during the test period and how it equated to a typical operational tank farm, it was important to know how the stored fuel's characteristics were changing. Fuel monitoring was scheduled for every quarter, with two samples being drawn: one from each bay's pump stand. A list of the measured properties and the associated specifications is given in Table 5.3.1:

Table 5.3.1   Fuel Quality Measured Properties

Measured Property	Specification
Density/API by Meter (15.5C/60F)	0.775 kg/L to 0.840 kg/L
(FSII) Fuel System Icing Inhibitor Content	0.15%
Electrical Conductivity	50 to 600 pS/m
Flash Point (Pensky-Martin)	38 °C
Karl Fisher (Total) Water Content	---

5.3.3   Climatic Conditions Monitoring

The climatic conditions are a critical part of the tank farm testing at SwRI in San Antonio, TX. The best way to determine the impact of temperature on tank performance is to correlate the climate back to tank skin temperature, material stretch and leak frequency and rate. The Weather Underground website was selected as the best source for this information. It offered hourly-through-monthly condition reporting as well as the ability to refer to historical records. In addition, it had a dedicated reporting station on site at SwRI, with internet and remote access through the web address, http://www.wunderground.com/q/zmw:78201.1.99999.

Figures 5.3.7 and 5.3.8 illustrate the site's capabilities with measurements recorded typically multiple times per hour.

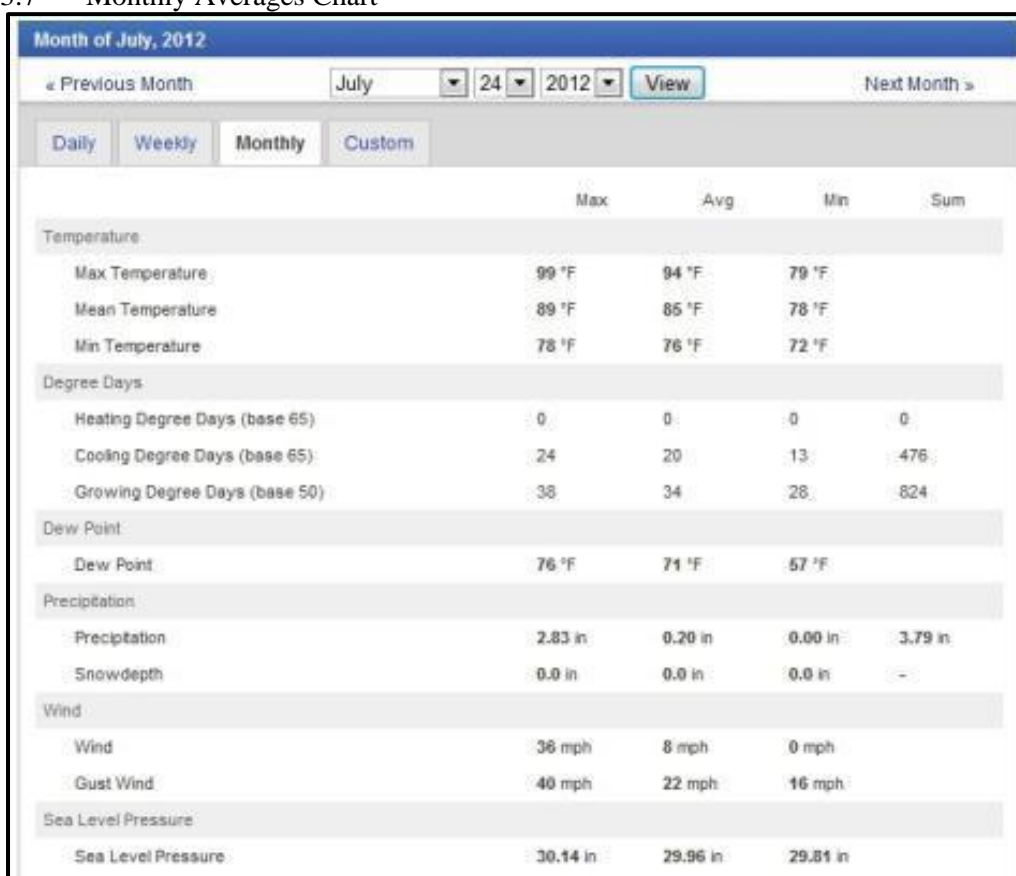Figure 5.3.7   Monthly Averages Chart

Figure 5.3.8   Monthly Continuous Strip Chart
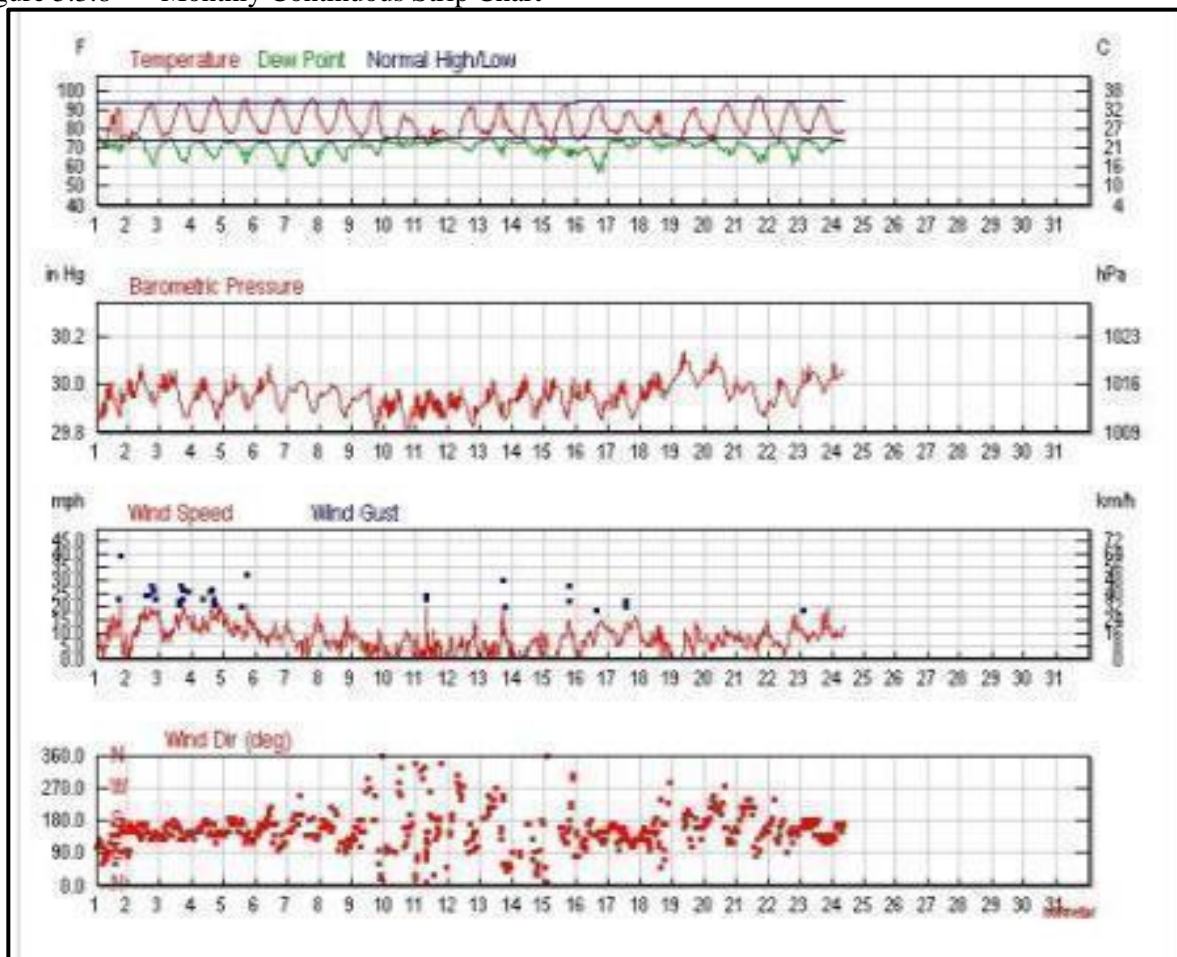
5.3.4   Instrumentation

5.3.4.1 Tank Height – Rod, Level and Measuring Stick

For a typical tank lot fabricated as part of a contract award, a strapping chart generally would be created for one tank and used for all of the tanks in the lot. For this effort, a separate strapping chart was generated for each of the 20 tanks. A look-up table was created from the strapping charts that gave heights for both a 3,000 gallon and a maximum overfill set point (Table 5.3.2).

Table 5.3.2   Strapping Chart Look-Up Table

Tank #	Standard Fill (gallons)	Height (in)	Max Fill (gallons)	Height (in)
50	50000	62	n/a	n/a
10	3000	46	3900	54 1/2
11	3000	46	3900	55 1/2
S-02	3000	35 1/8	4000	52 1/8
13-1	3000	35 1/4	4022	54 1/2
14	3000	33 3/8	4001	51
15-1	3000	33 5/8	4000	51
16	3000	36 1/2	4000	54 1/8
17	3000	37	4011	56 1/4
18	3000	37 1/4	4000	56 1/4
19	3000	37 1/2	4000	55 1/4
20	3000	34 3/4	4000	53 3/8
21-1	3000	33 5/8	4000	51 1/2
22	3000	34 5/8	4000	52 1/4
23-1	3000	34 1/4	4000	52 5/8
24-1	3000	24 7/8	4508	43 1/4
25-2	3000	25 1/8	4502	42 1/4
26-1	3000	25 3/8	4500	46
27-1	3000	41	4000	52 1/2
28-1	3000	26 3/4	4500	45 1/2
29-1	3000	29 1/2	4502	53 5/8

As a backup to the flow meter, the strapping chart was referenced to set the volume by the height. A telescoping rigid ruler was utilized to get the height measurement off a straight piece of conduit by resting it on the peak of the tank near the vent with a bubble level attached. The base of the rigid ruler was rectangular in footprint allowing the operator to maintain a consistent vertical orientation. Observed variance with vertical orientation was typically within 1/8". To ensure that the measurement was repeatable, an "X" was drawn onto the berm liner next to tank.

5.3.4.2 Pump Pressure and Volume Totalizing

Discharge flow rate or total volumetric flow and pressure are critical measurements to monitor for understanding the acceptable operation of the pump. Optimizing the flow rate versus pressure allows for shuttling tanks in the most reasonable amount of time. For this network, it was found that a discharge pressure of 15 – 25 psig and a flow rate from 80 – 160 gpm were typically acceptable. A glycerin-filled, shockproof pressure gage was installed on the discharge line of the pump (Figure 5.3.9).

Figure 5.3.9   Pump Discharge Pressure Measurement

5.3.4.3 Tank Volume

5.3.4.3.1 Flow Meters

Initially, the preference from DLA was to measure directly total volumetric flow at the inlet of each tank. A Sierra Innova-Sonic Model 210i ultrasonic flow meter (Figure 5.3.10) was selected to meet that expectation because it could be mounted independently on each tank being measured. This meter is a non-contact device that utilizes a set of ultrasonic transducers that must be mounted to the exterior of the pipe carrying the fluid. A four-foot long, three-inch ID aluminum flow pipe was installed prior to the inlet of each to provide the fully developed flow regime needed for reliable measurement (Figure 5.3.11). Based on temperature curve provided by SwRI for JP-8, both fluid velocity and viscosity could be entered to compensate for temperature differences across a shuttle run.

Figure 5.3.10   Sierra 210i Ultrasonic Flow Meter

Figure 5.3.11   Flow Pipe with Ultrasonic Transducers Attached

The Innova-Sonic Model 210i gave reasonable measurements when shuttling from an over-filled to an under-filled tank. However, repeatability measurement issues surfaced when shuttling fuel into an empty tank from overfilled tanks. For the first half of the tank fill, the volume total was quite reasonable when compared to the strapping chart. When filling the second half of the tank, the meter would measure short, typically as much as 20%.

Each pump stand was outfitted with a flow pipe so that the discharge volumetric rate could be verified at the pump. Since there was not an appreciable difference in flow measurement between the pump stand and the tank inlet, it was decided that a meter installed directly on the pump stand would be acceptable.

To provide effective volumetric measurement verification across multiple meters, two different types were selected for use. A Sierra 241Innova-Mass Vortex Mass Flow meter (MFM) was selected as a direct replacement for the ultrasonic meter (Figure 5.3.12). It was installed on pump stand 2 in the Twenty Bay. For the Teen Bay, a fuel industry standard Omega FTB380 Series Turbine flow meter was installed (Figure 5.3.13).

Figure 5.3.12   Sierra 241   Figure 5.3.13   Omega FTB380 Series Turbine Flow Meter
Vortex MFM

5.3.4.4 Tank Stretch Measurement

5.3.4.4.1 Laser Calipers for Stretch Measurement

Haglof Mantax Black / green laser calipers were selected to make the panel warp and fill stretch measurements (Figure 5.3.14). The green laser calipers allow the operator to take non-contact measurements from a distance with the laser sights, if necessary. However, the direct slide caliper measurement was specified as the preferred method.

Figure 5.3.14   Haglof Mantax Black / Green Laser Calipers

5.3.4.5 Tank Skin Temperature Measurement

For environmental temperature impact on tank performance, a Wahl z50 Thermal Image Camera was chosen (Figure 5.3.15). To capture the entire tank profile, a wide angle lens adapter was added and the two calibrated as a system. The supporting Wahl image processing software gave the capability of tank skin area or line averaging. The tank skin temperature averages were correlated to the ambient temperature condition to determine the percent contribution of temperature to tank material stretch.

Figure 5.3.15   Wahl z50 Thermal Image Camera with Wide Angle Lens

5.3.4.6 Leak Documentation Method

Leaks were detected primarily by two methods: visual inspection and the use of 3M Petroleum Sorbent Pads. The 3M Petroleum Sorbent Pads proved critical if there were any questions regarding the presence of JP-8. For example, after a rain it was not uncommon for under-filled tanks to have water seep beneath them. Once these tanks were over-filled per the shuttling schedule, the water underneath the tank was squeezed out. This gave the appearance that the tank might be leaking fuel from the bottom. When in doubt, the 3M Petroleum Sorbent Pads were used to confirm the presence or absence of JP-8. The pad would turn a bright yellow when it absorbed JP-8 into the cloth; however, water would have no effect.

For visual evaluation, the TECHNICAL BULLETIN FOR COLLAPSIBLE FABRIC FUEL TANKS (Department of the Army) – BRAG (TB 10-5430-253-13 – DEC 2009), was utilized to identify and classify the leaks. The only departure from this method was the addition of corners as a separate feature into the classification scheme. The overall document was summarized into a two to three- page document for ease in field use (see Appendix N).

5.3.4.7 Database for Field Measurement Management

Based on the design and information provided by the Seaman Corporation, Southwest Research Institute developed a Microsoft Access database to serve as the main portal for data entry in the field. This was critical when considering the projects aggressive measurement schedule and overwhelming amount of data. The database was loaded onto a Windows based tablet for ease of recording at the tank farm. It allowed the operator to not only directly input measurements while in the field, but also pictures and other critical documentation relative to leaks and their history.
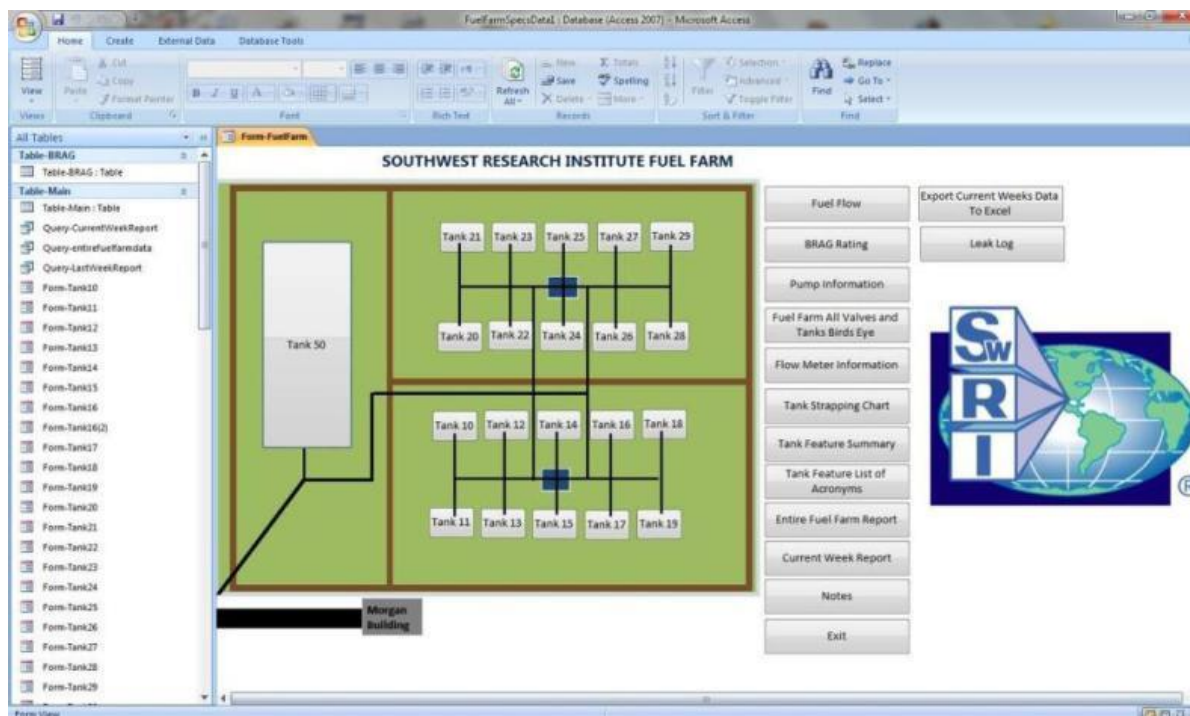
Further detail on the database can be found in Appendix O.

5.4   Data Summary

5.4.1   Stretch Measurements

5.4.1.1 Daily Overfill Stretch Measurements – Approach Established in FY2008 Program

In the FY2008 CFT program, it was proven that the peak stretch found in larger tanks (e.g., 50,000 and 210,000 gallons) could be replicated in a 3,000-gallon tank by exceeding the recommended tank fill volume by 30-50%. According to the FEA analysis, "Failure Analysis and Alternative Solutions for Collapsible Fabric Tanks," the maximum in-plane stress for a 50,000-gallon tank was 14610 psf. For the given tank material thickness, the load in the fabric equates to 50 lbs_f/inch (1.7% warp and 4.5% fill stretch, Figure 5.4.1). The FEA results were used since actual tank stretch measurements were not available on the larger tanks with the 1940 PTFF material. The 1940 PTFF Biaxial Stretch curve was generated to 75 lbs_f/inch. It was believed that doing this would conservatively allow for any greater stretch in larger tanks than what may have been predicted by the FEA model. During the 3,000-gallon model tank overfill testing, a 150% tank volume (4,500 gallons) generated a fill stretch of 9.4% and a warp stretch of 3.8% which was above the FEA derived value.
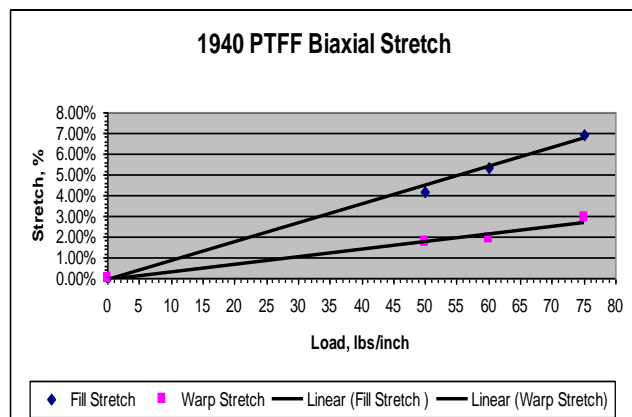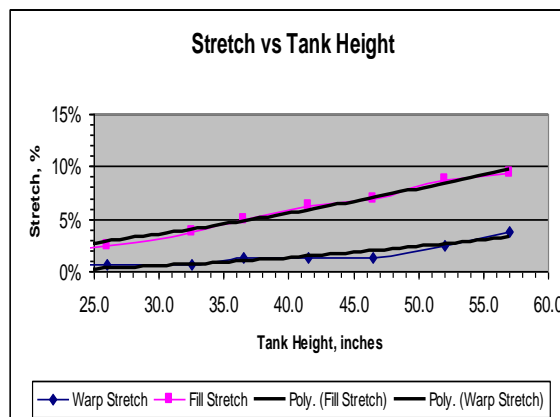
Figure 5.4.1 – 1940 PTFF Tank Material   Figure 5.4.2 – Model Tank Height versus
Biaxial Stretch   % Stretch

For the field test, it was critical to verify the stretch measurement in an actual 50,000-gallon tank with JP-8. This was done to check the FY2008 over-fill concept, the use of the FEA for establishing a minimum and to verify actual stretch prior to the onset of the performance testing of the 3,000-gallon tanks. A 50,000-gallon tank was added to the study for this purpose and to serve as emergency back-up storage and/or shuttling reservoir. This tank was the first deployed at the test site. It was filled first to the 100% target volume and allowed to sit and equilibrate with the environment for three days. Measurements were then made on the tank to verify the peak warp and fill stretch values. The results of this measurement are shown in Figure 5.3.7. Per the graph, the peak fill stretch measured was 7.7% and the associated peak warp stretch was 1.4%. While the warp stretch was slightly less than the FEA calculated value the fill stretch was considerably more. When checked against the biaxial stretch curve (Figure 5.4.1), this would result in loads of 83 lbs$_f$/inch for the fill direction and 41 lbs$_f$/inch for the warp direction. Therefore a peak fill stretch of 7.7% (from the 50K measurement) and a peak warp stretch of 1.7% (from the FEA calculation) were set as target peak thresholds for the 3,000 gallon tank overfills.

During fabrication of the 3,000 gallon field tank designs all of the tanks were filled with water and a strapping chart generated for each. A volume of 150% (50% over the 3,000 gallon design) was designated as the maximum fill condition. Tanks were filled either to that volume or to the point where water overflowed from the top center vent. Based on this method, the following maximum fill tank volumes were achieved and can be found in the master strapping chart, Table 5.3.2 or in Table 5.4.1:

Table 5.4.1 – Tank Maximum Fill Volume and Condition

Tank #	Maximum Fill Volume (gallons)	Max Volume Determination
10 /11	3,900	Vent overflow @ 130% volume
12S – 23, 27	4,000	Vent overflow @ 133% volume
24 – 26, 28, 29	4,500	150% volume

During fabrication water testing and strapping chart creation, peak stretch was verified for either vent overflow or achieving 150% fill. A fill peak stretch measurement of >7.7% and a warp peak stretch of >1.7% were set as target values and noted as achievable on all tanks. Tanks 10 and 11, based on a commercial fabricators design, had a manway / filler protective flap welded at the "C" and "D" panels, making the measurement readings questionable. This exception will be discussed further in the following section.

A description of the tank features is summarized for reference in Table 5.4.2. It is broken down by panel seam, closing seam, corner, fitting and seam tape types.

Table 5.4.2 – Tank Feature Summary

Tank #	Tank Design	Panel Seam Type	Closing Seam Type	Corners Type	Fittings Type	Seam Tape Type
50	Fabricator	Shingle Overlap	Bottom Over Shear Seam	Tapered Triangle	Per Fabricator	Per Fabricator
10 / 11	Fabricator	Shingle Overlap	Bottom Over Shear Seam	Tapered Triangle	Per Fabricator	Per Fabricator
12	Fabricator	Per Fabricator	Per Fabricator	Per Fabricator	Per Fabricator	Per Fabricator
13	Fabricator	Alternate Overlap	Fold Over Prayer Weld	Per Fabricator	Per Fabricator	Per Fabricator
14 / 15	Fabricator	Double Butt Seam	Double Butt Seam	Square Welded Corner with Clamp	Standard	Butt Seam
16		Shingle Overlap	Bottom Over Shear Seam	Square Welded Corner with Clamp	Standard	Standard
17		Alternate Overlap	Bottom Over Shear Seam	Square Welded Corner with Clamp	Standard	Profile
18		Shingle Overlap	Bottom Over Shear Seam	Square Welded Corner with Clamp	Bidirectional Doubler	1" Reinforced
19		Alternate Overlap	Bottom Over Shear Seam	Square Welded Corner with Clamp	O-Ring Compression	2" Reinforced
20	TK3K2 Phase I	Alternate Overlap	Fold Over Prayer Weld	Square Welded Corner with Clamp	Standard	Standard
21		Shingle Overlap	Fold Over Prayer Weld	Square Welded Corner with Clamp	Bidirectional Tripler	Profile
22		Double Butt Seam	Double Butt Seam	Square Welded Corner with Clamp	Bidirectional Doubler	Butt Seam
23		Double Butt Seam	Double Butt Seam	Square Welded Corner with Clamp	O-Ring Compression	Butt Seam
24	Canoe	Shingle Overlap	Shingle Overlap w/ T-Seams	Semicircular Cap	Bidirectional Tripler	1" Reinforced
25	Belly Band	Alternate Overlap	Shingle Overlap w/ T-Seams	No Corners Present	Standard	Profile
26	Trap 4	Shingle Overlap	Shingle Overlap w/ T-Seams	Trapezoid Angle	Standard	1" Reinforced
27	Quonset Hut	Shingle Overlap	Double Butt Seam	No Corners Present	Bidirectional Tripler	Butt Seam
28	6 Panel Trap "Dog Bone"	Alternate Overlap	Shingle Overlap w/ T-Seams	Trapezoidal Angle	O-Ring Compression	2" Reinforced
29	Transverse T	Alternate Overlap	Double Butt Seam	Square Welded Corner with Clamp	Standard	Butt Seam

5.4.1.2 Baseline (100%) and Baseline Overfill (130-150%) Initial Stretch

Once the 50,000 gallon tank confirmatory measurement was made, the process of shuttling fuel to each of the twenty test tanks began. All twenty of the tanks were initially filled to 3,000 gallons and allowed to sit and equilibrate with ambient conditions for at least three full days. At the end of the settling period, a round of warp and fill stretch measurements on all accessible panels "A" through "G" were made to establish a baseline for 100% target volume fill.

The process of weekly over-fill shuttling was then initiated with the odd-numbered tanks being overfilled first. The tanks were allowed to stretch and settle for a day prior to initial overfill stretch measurements being taken. The process was then repeated allowing for overfill and stretch measurement of all of the even-numbered tanks.

A direct comparison of all 3,000 and overfill baseline stretch measurements are depicted in Figures 5.4.3 through 5.4.30. The comparisons are broken up by similar tank types as listed in Table 5.4.3. For each tank type, a representative stretch panel measurement ("A" – G") location schematic is provided. For any tank not shown, a schematic is located in Appendix G. Schematics not shown have the same panel layout location to the other similar tanks in the group. A few initial overfill stretch measurements were less than the original peak values encountered during fabrication. It was assumed this was due to some initial tank stretch and settling and would need to be verified across the test period.

Table 5.4.3 – Similar Tank Design Classifications for Baseline and Overfill Stretch Comparison

Tank #	Tank Type	Design Figures	Table Figures	
			Baseline	Overfill
10 / 11	Fabricator Design	5.4.3, 5.4.4	5.4.5	5.4.6
12S / 13	Fabricator Design	5.4.7, 5.4.8	5.4.9	5.4.10
14 / 15	Double Butt Seam	5.4.11, 5.4.12	5.4.13	5.4.14
16 – 19	FY2008 Standard Design Tank	5.4.15, 5.4.16	5.4.17	5.4.18
20 – 23	FY2008 Standard Design Tank	5.4.19, 5.4.20	5.4.21	5.4.22
24 – 29	Prototype Tanks	5.4.23 – 5.4.28	5.4.29	5.4.30

Figure 5.4.3 – Tank 10 Panel Measurement Layout   Figure 5.4.4 – Tank 11 Measurement Panel Layout
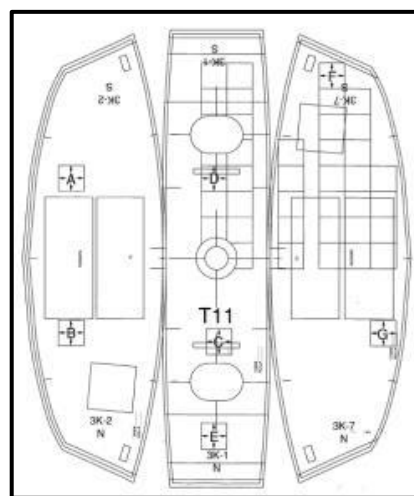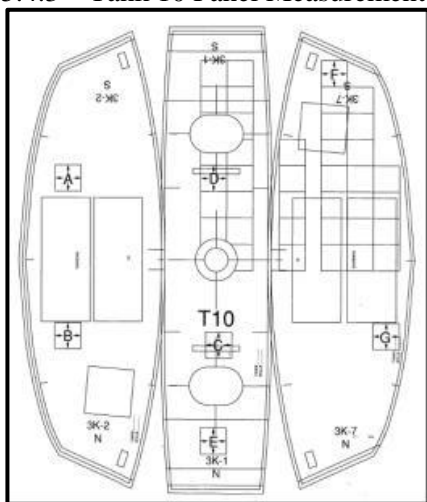
Figure 5.4.5 – Tank 10/11 3K Baseline Stretch Measurements

Figure 5.4.6 – Tank 10/11 3.9K Overfill Stretch Measurements
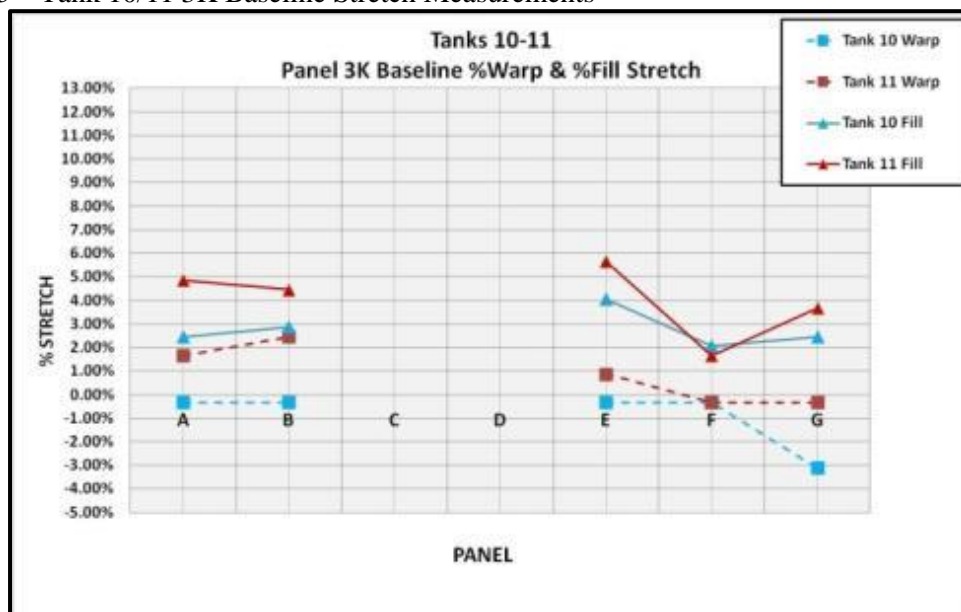
Figure 5.4.7 – Tank 12S Measurement Panel Layout
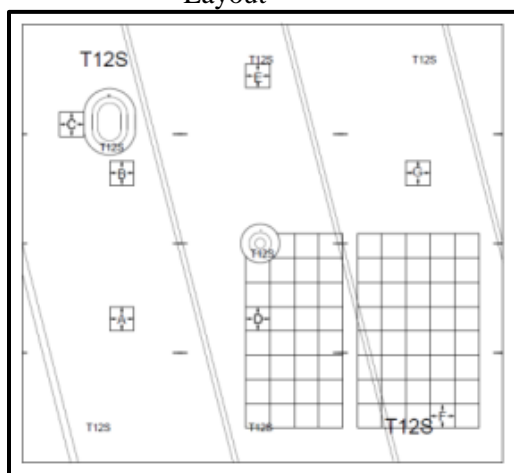
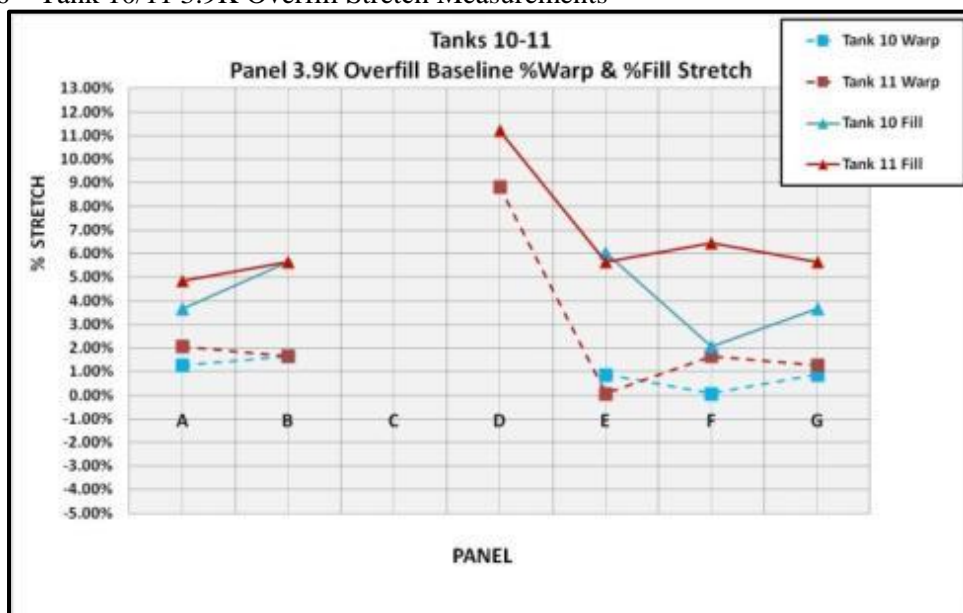Figure 5.4.8 – Tank 13 Measurement Panel Layout

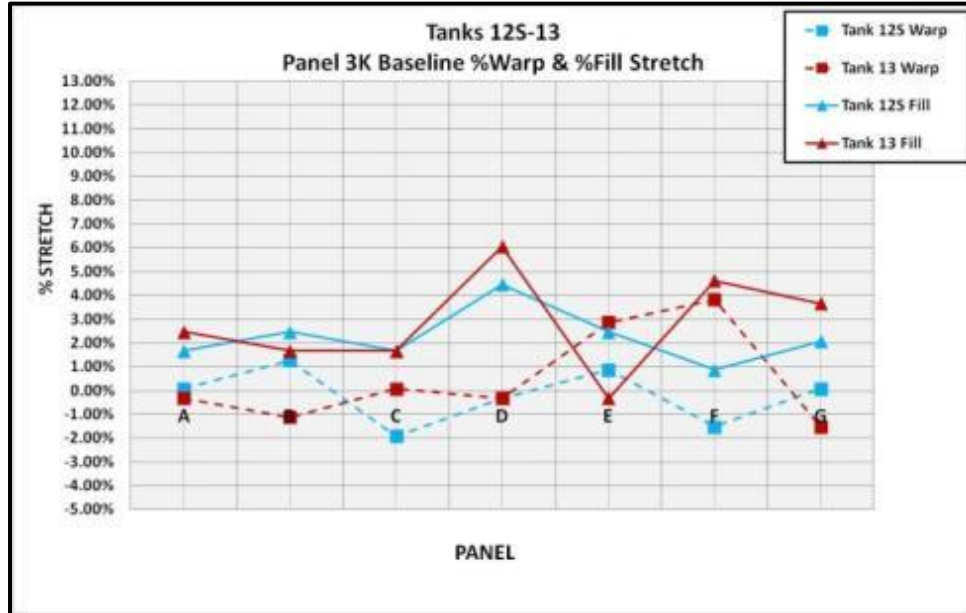Figure 5.4.9 – Tank 12S/13 3K Baseline Stretch Measurements

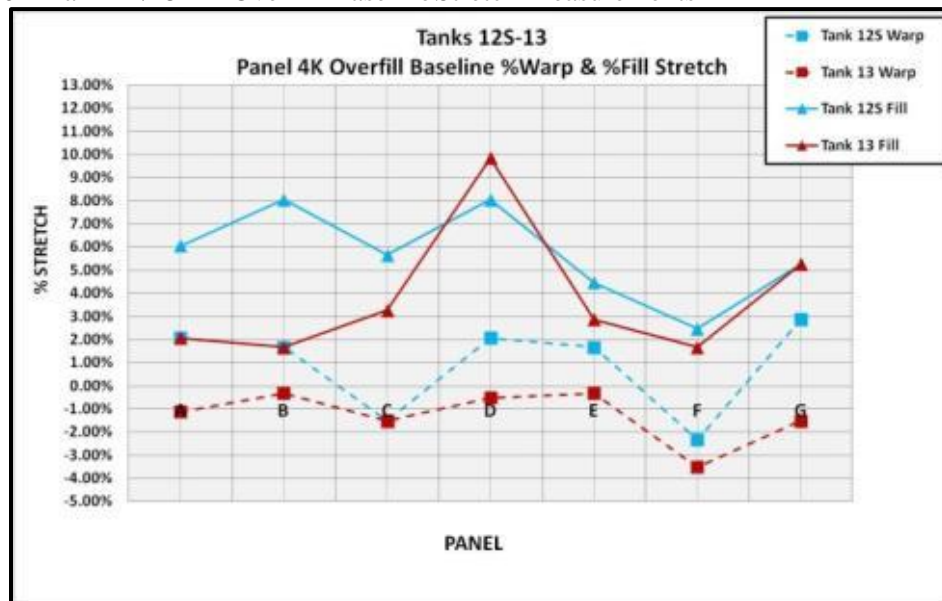Figure 5.4.10 – Tank 14/15 4K Overfill Baseline Stretch Measurements

Figure 5.4.11 – Tank 14 Measurement Panel Layout Figure 5.4.12 – Tank 15 Measurement Panel Layout
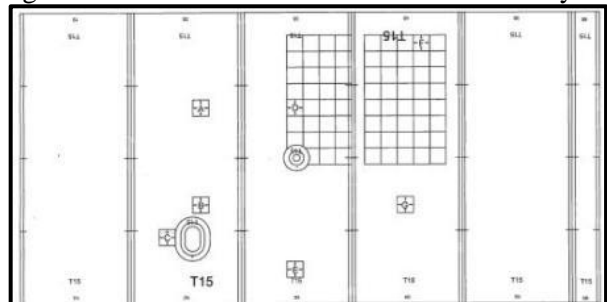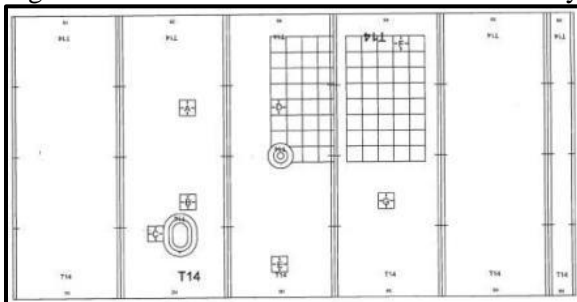
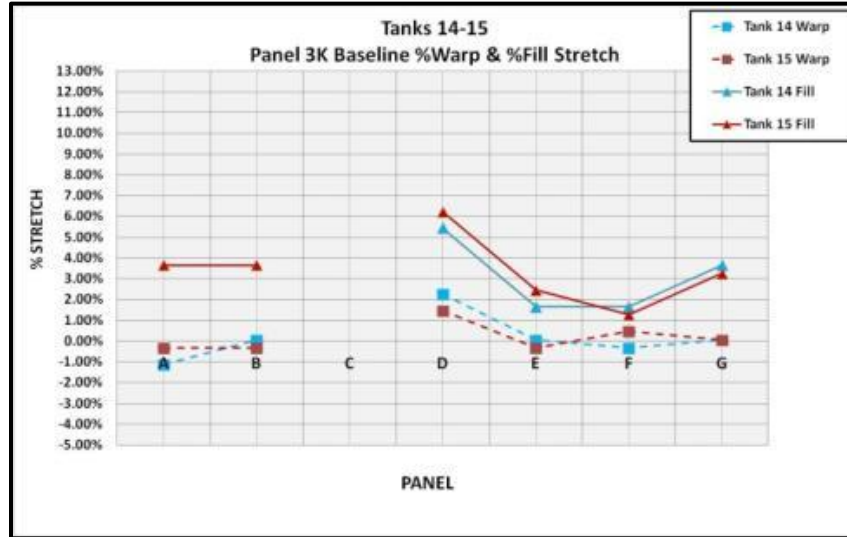Figure 5.4.13 – Tank 14/15 3K Baseline Stretch Measurements

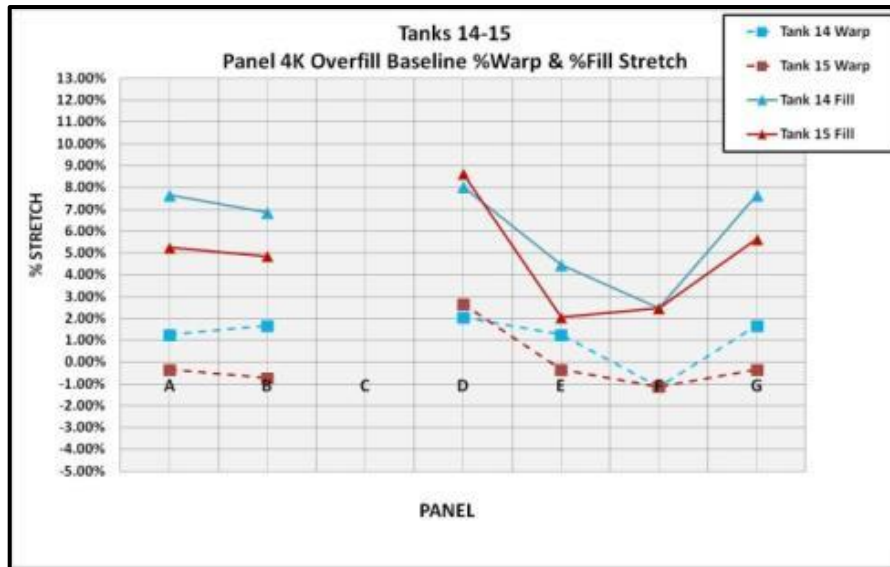Figure 5.4.14 – Tank 14/15 4K Overfill Baseline Stretch Measurements

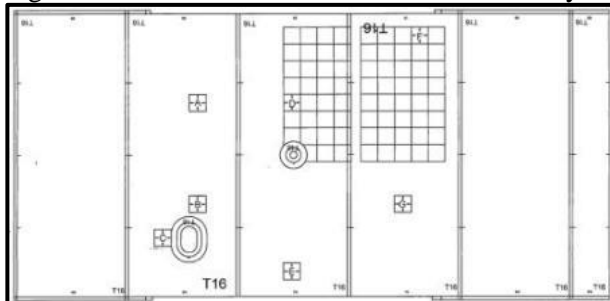Figure 5.4.15 – Tank 16 Measurement Panel Layout Figure 5.4.16 – Tank 19 Measurement Panel Layout
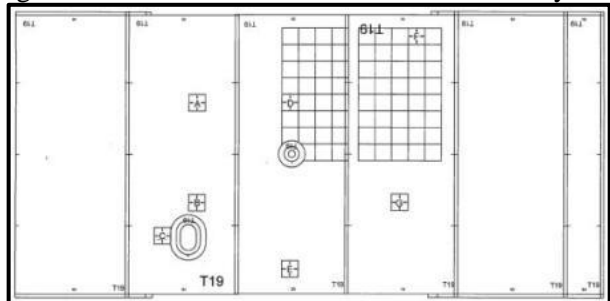
Figure 5.4.17 – Tank 16-19 3K Baseline Stretch Measurements
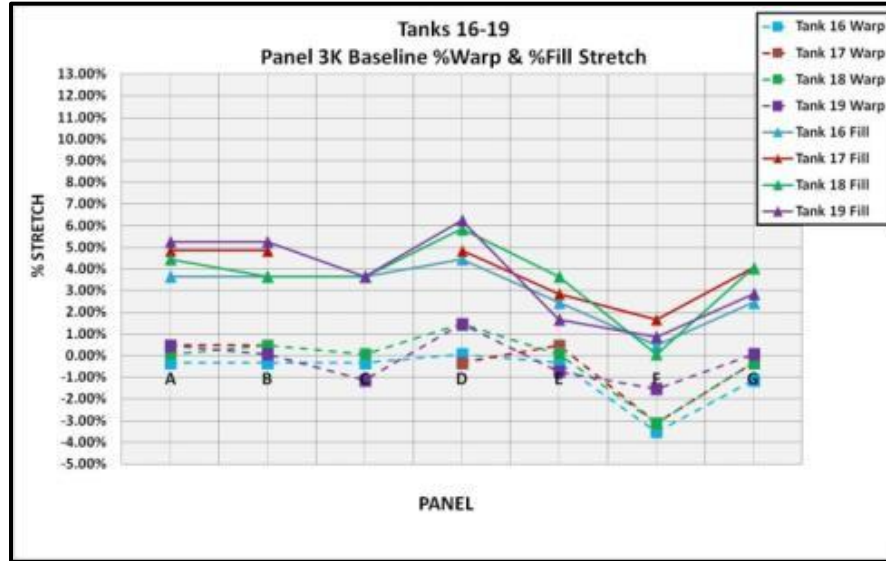

Figure 5.4.18 – Tank 16-19 4K Overfill Baseline Stretch Measurements

Figure 5.4.19 – Tank 20 Measurement Panel   Figure 5.4.20 – Tank 23 Measurement Panel
                    Layout   Layout

Figure 5.4.21 – Tank 20-23 3K Baseline Stretch Measurements

Figure 5.4.22 – Tank 20-23 4K Overfill Baseline Stretch Measurements

Figure 5.4.23 – Tank 24 Measurement Panel Layout Figure 5.4.24 – Tank 25 Measurement Panel Layout

Figure 5.4.25 – Tank 26 Measurement Panel Layout

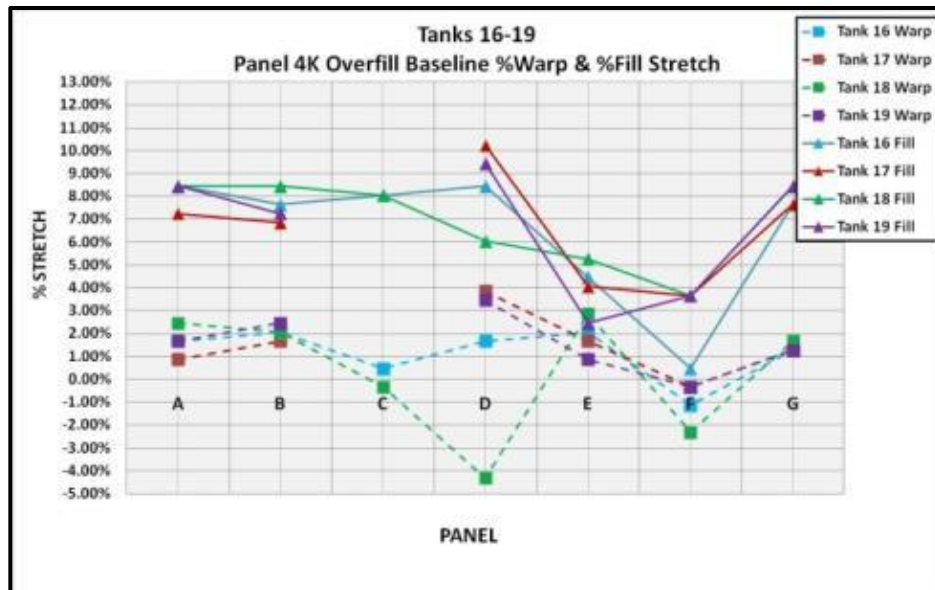
Figure 5.4.26 – Tank 27 Measurement Panel Layout

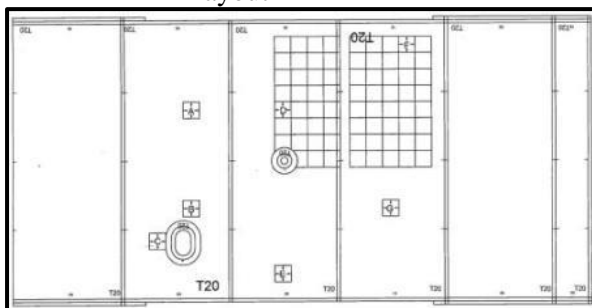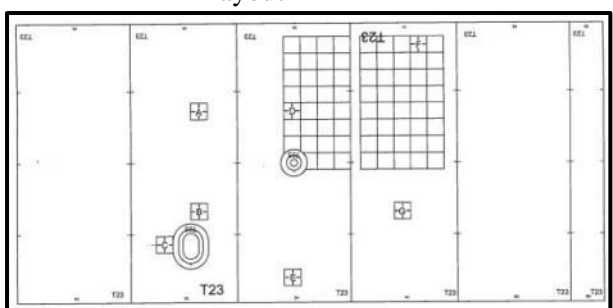Figure 5.4.27 – Tank 28 Measurement Panel Layout
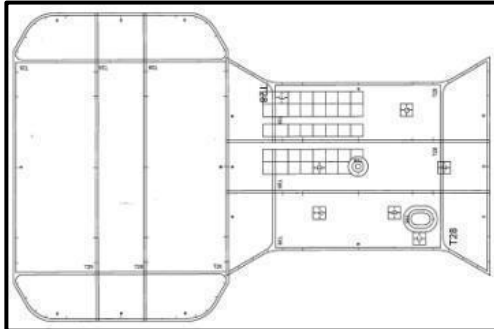
Figure 5.4.28 – Tank 29 Measurement Panel Layout

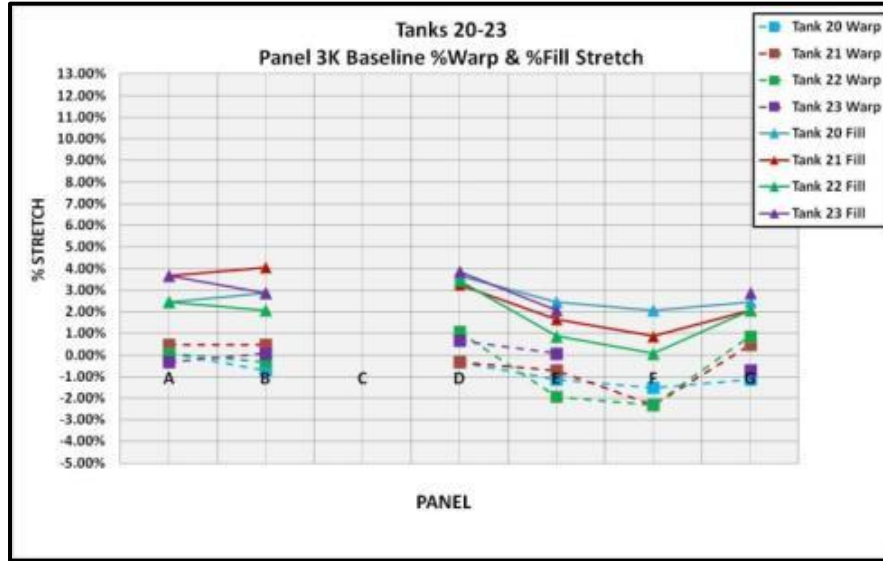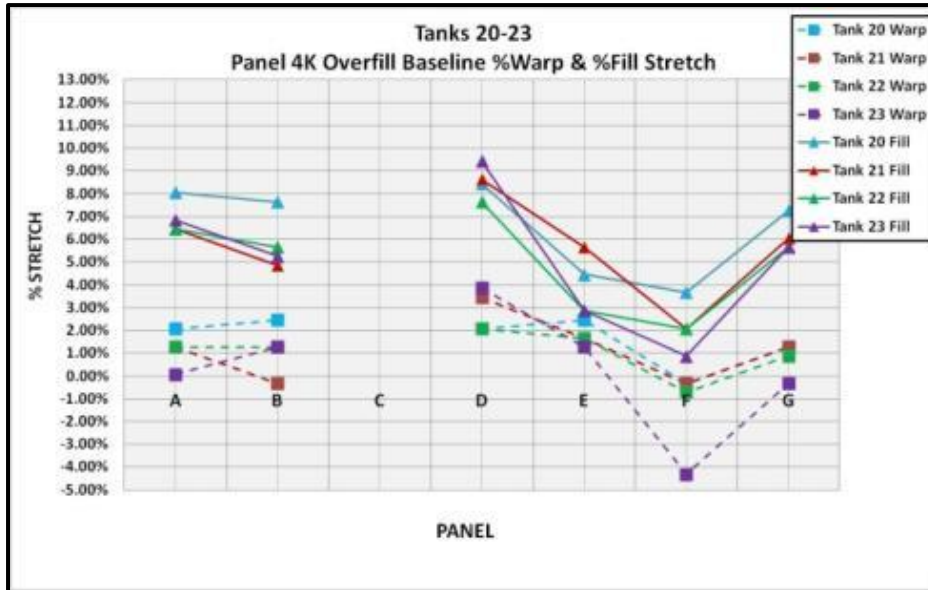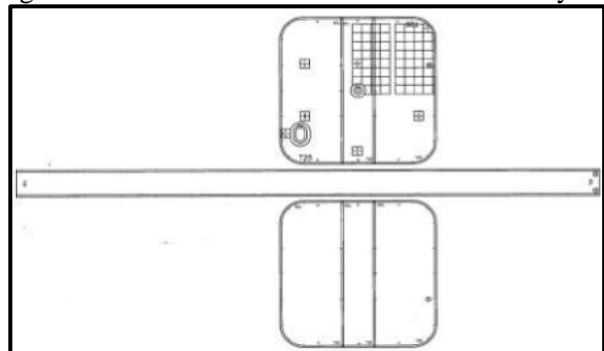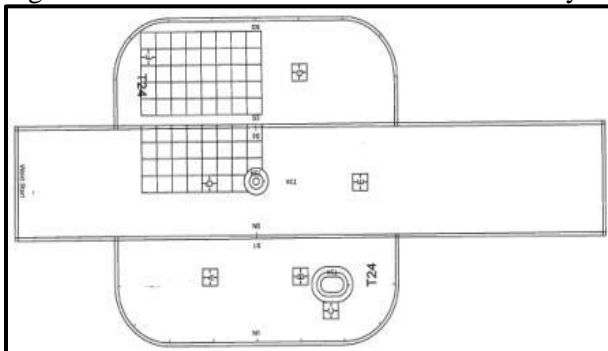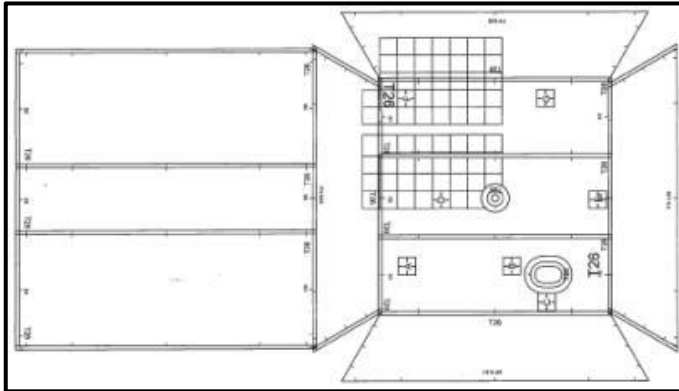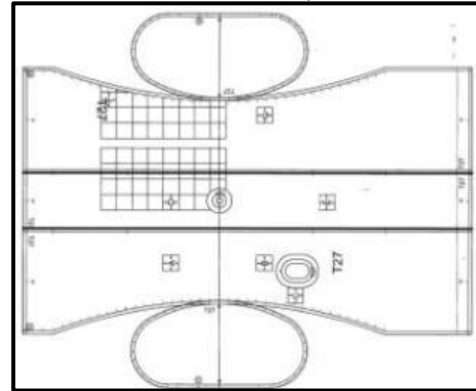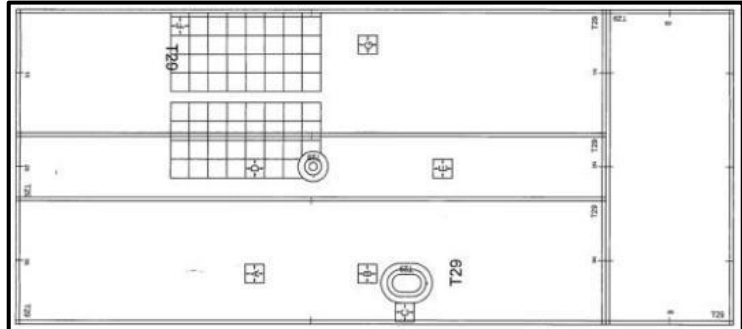Figure 5.4.29 – Tanks 24-29 3K Baseline Stretch Measurements
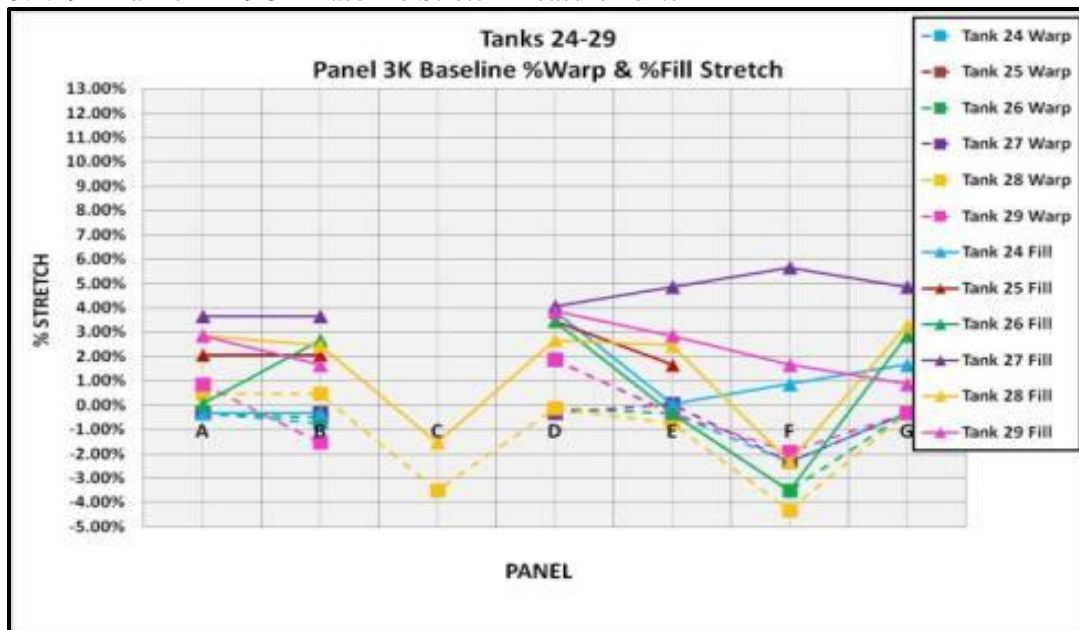
Figure 5.4.30 – Tanks 24-29 4-4.5K Overfill Baseline Stretch Measurements
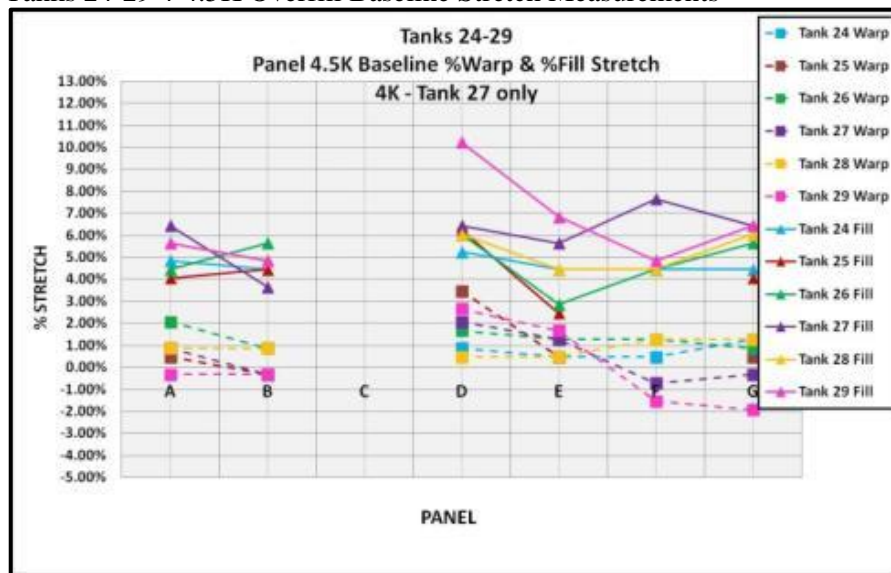
The initial baseline overfill stretch measurements of most of the tanks met minimum requirements >7.7% fill and >1.7% stretch. The major exceptions occurred in the prototype designs (Tank 24-29). These tanks were at or near maximum overfill until fuel exited the vent resulting in an undesirable outcome. The testing had just initiated and it was decided to maintain the established fill level maximums in light of increasing summer temperatures. The tank fill stretch maximum in an overfill condition exceeded the 3K fill stretch by 50% - 250%, dependent greatly on tank design.

5.4.1.3 Daily Overfill Measurements

Even or odd overfill tank shuttling and measurement occurred in alternating weeks from test onset through completion. The only exceptions which occurred were due to site visits with additional on-site testing or inclement weather conditions. Toward the end of the summer of 2012 (especially from July through September) temperatures frequently exceeded 100 °F. As was anticipated, this lead to increased stretch and all tanks were measured at peak values in excess of the target fill (>7.7%) and warp stretch (>1.7%).

After the first six months of shuttling, tanks were drained as completely as possible (a few inches of fuel remaining) and the fill and warp panels were measured to check for any zero stretch baseline offset. The results are shown in Figure 5.4.31.

Figure 5.4.31 – Zero Fill Baseline Stretch
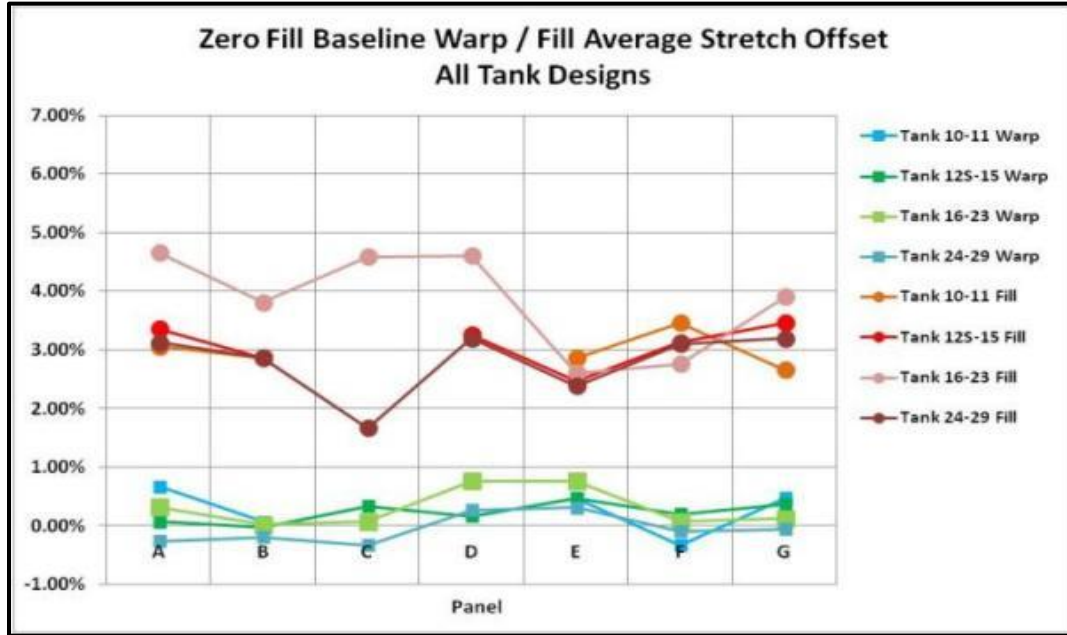
Average zero stretch values across the tanks were determined and plotted. Generally, fill zero stretch was 3%. The exceptions were the FY2008 design tanks (16-23) which exceeded 4% for panels A, C and D. Average warp zero stretch ran typically from -0.5 to 1.0% across all tanks. This illustrates that, after the tanks initial fill, permanent material stretch occurs dependent on tank design with an offset of 3-5% in the fill direction and -0.5-1% in the warp direction.

After the 18-month test period, the average monthly stretch data for each measurable panel on every tank was graphed. A few representative graphs are shown in Figures 5.4.32 – 5.4.37. A summary of all graphs is located in Appendix R. On each graph, the average monthly temperature is plotted in blue and shown on the right vertical axis to highlight any temperature dependency on stretch. All tanks with the exception of 10 and 11, where panels C and D were not typically measurable, exhibited the same behavior. During the first three to six months of testing, fill stretch peaked then stabilized and equilibrated to a reduced value throughout the remainder of the testing. It appears that the panel stretch reduces as the material stretch offset (zero fill baseline) becomes permanent three to six months after the test onset.

Another notable trend is the spread of stretch values that occur with differing tank designs. A typical pillow tank design (Tanks 16-23) will have a much broader maximum to minimum panel fill stretch range (5-7% typically) than a prototype tank (3% typically). For example, looking at the Fill Stretch trend for Tank 13, the difference between panel "D" and panel "F" is 8-9% overall, from approximately 11 to 2% for the first three months to 10 to 1.5% for the last three months (Figure 5.4.33). Further evidence of this can be seen in the Tank 19 graph (Figure 5.4.35). By comparison, a prototype, Tank 28, has a fill stretch range of 5% in the beginning down to 3% after October 2012 (Figure 5.4.37).

Figure 5.4.32 – Tank 13 Panel Warp Stretch Trend over test period
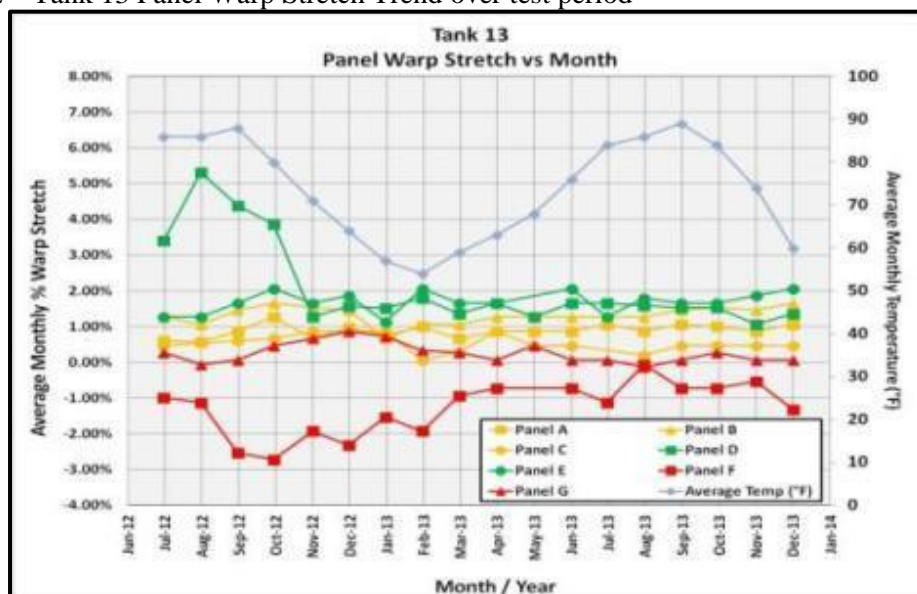
Figure 5.4.33 – Tank 13 Panel Fill Stretch Trend over test period
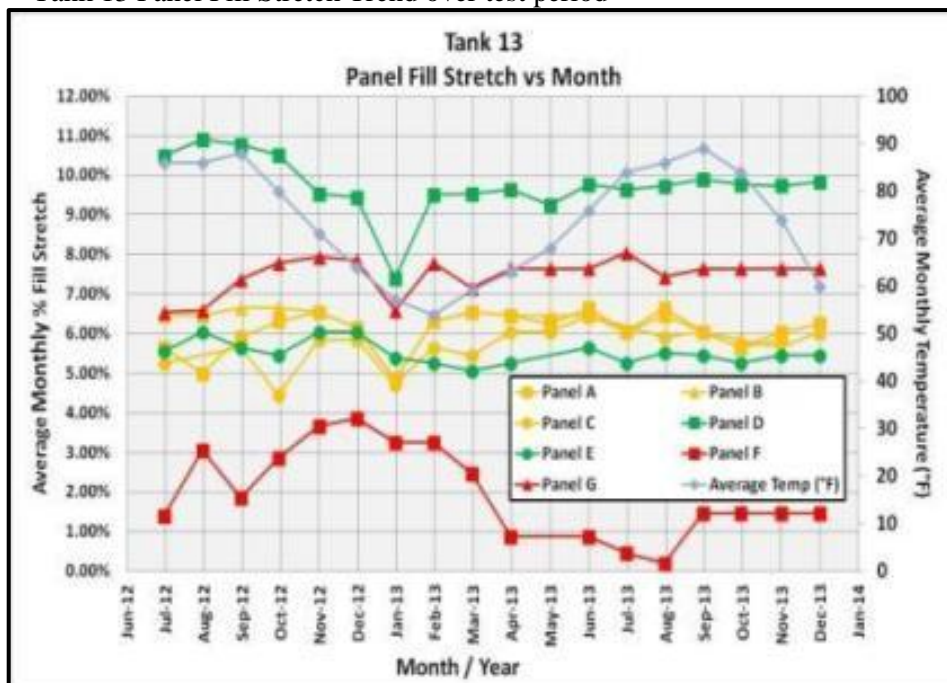
Figure 5.4.34 – Tank 19 Panel Warp Stretch Trend over test period
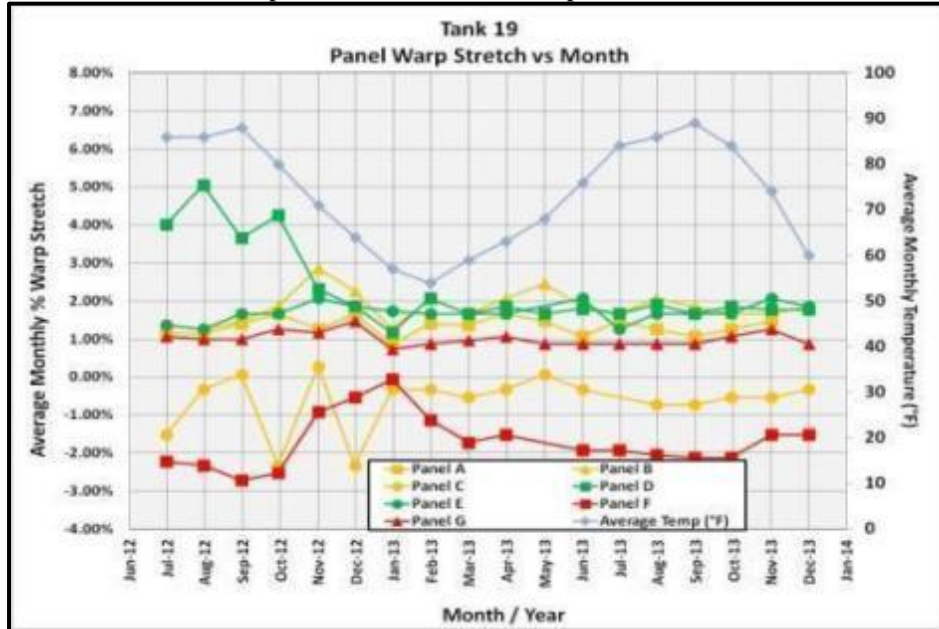
Figure 5.4.35 – Tank 19 Panel Fill Stretch Trend over test period
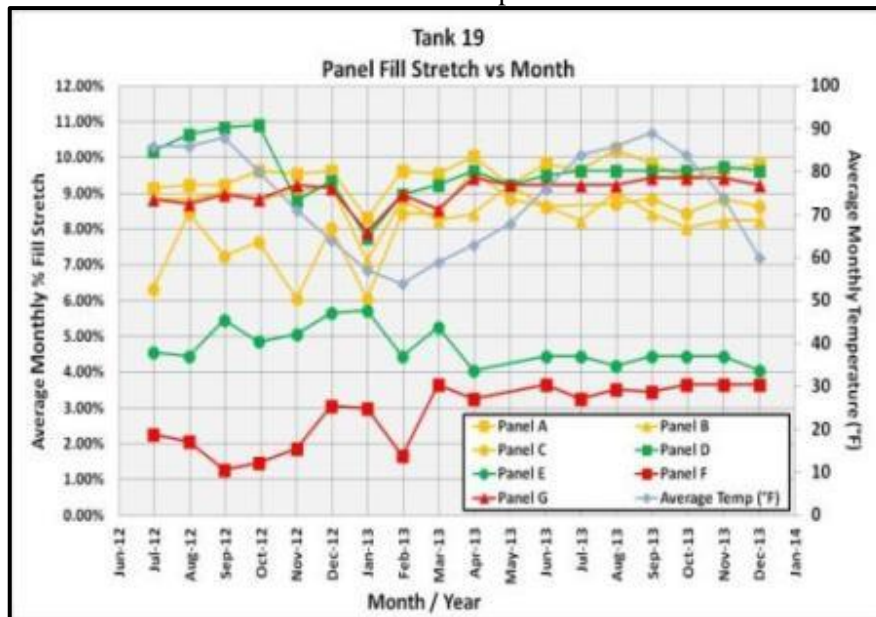
Figure 5.4.36 – Tank 28 Panel Warp Stretch Trend over test period
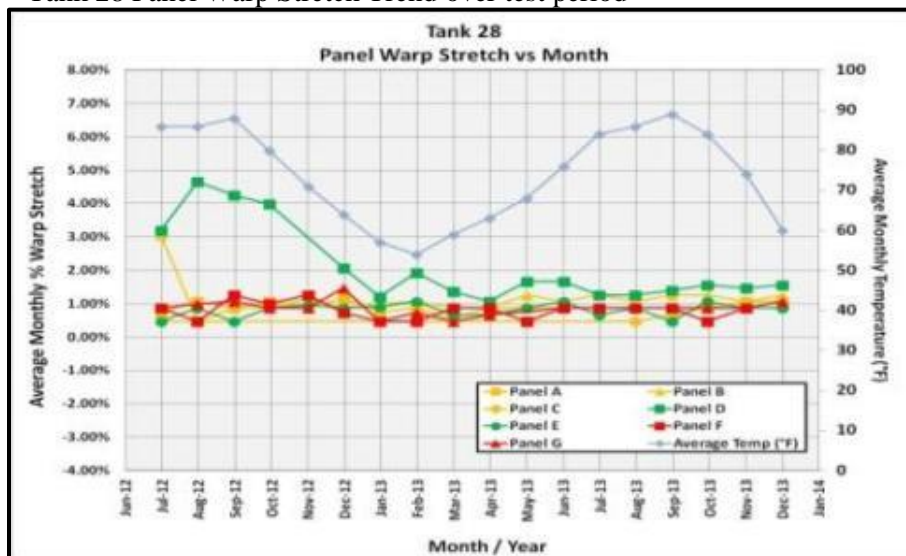
Figure 5.4.37 – Tank 28 Panel Fill Stretch Trend over test period
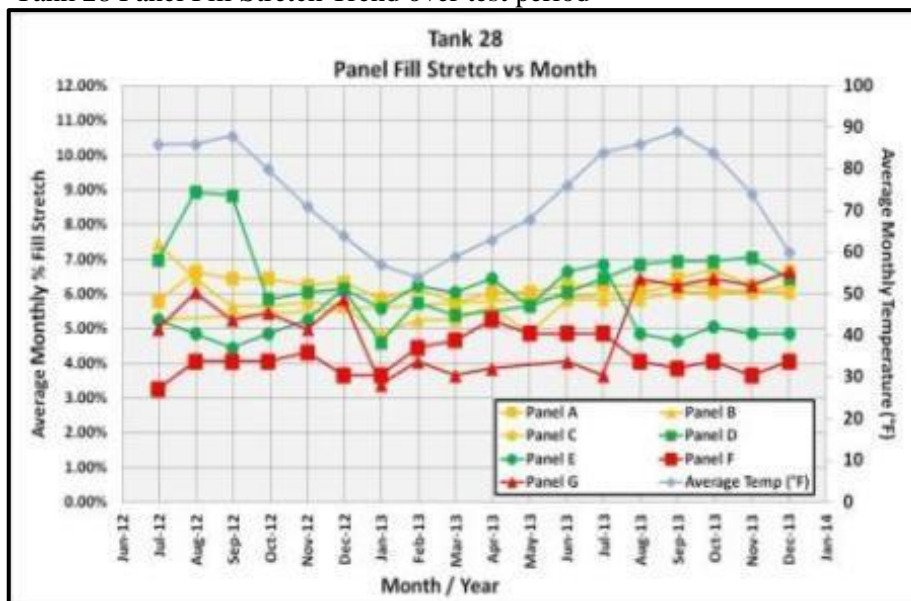
For each tank, a plot of overfill warp and fill average stretch and standard deviation across the entire test period for each panel location was created (Figures 5.4.38 – 5.4.57). This was done to better understand the differences in overall tank designs and tank features by effectively creating a tank stretch contour plot across all the measurement panels. In addition, initial fill stretch and temperature variability impacts are still accounted for in the standard deviations associated with the average stretch values.

For Tanks 10 and 11, the results are somewhat misleading due to the inability to get consistent readings on panels "C" and "D". These panels are known to be where maximum stretch occurred (Figure 5.4.6). However, the manway cover flaps prevented a consistent measurement. Of the panels measured, the tank did show repeatable stretch with little variation across the surface in either the warp or fill direction.

Figure 5.4.38 – Tank 10 Average Panel Stretch across Test Period
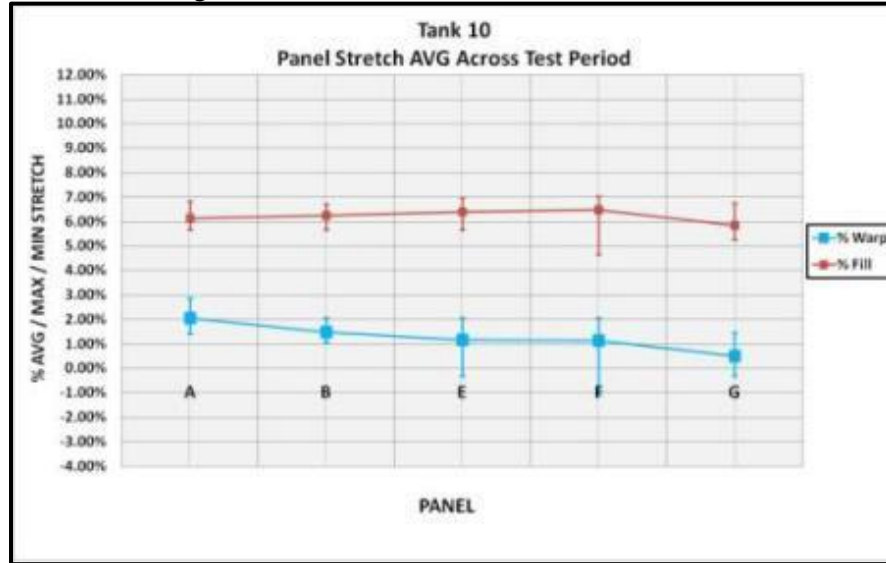
Figure 5.4.39 – Tank 11 Average Panel Stretch across Test Period
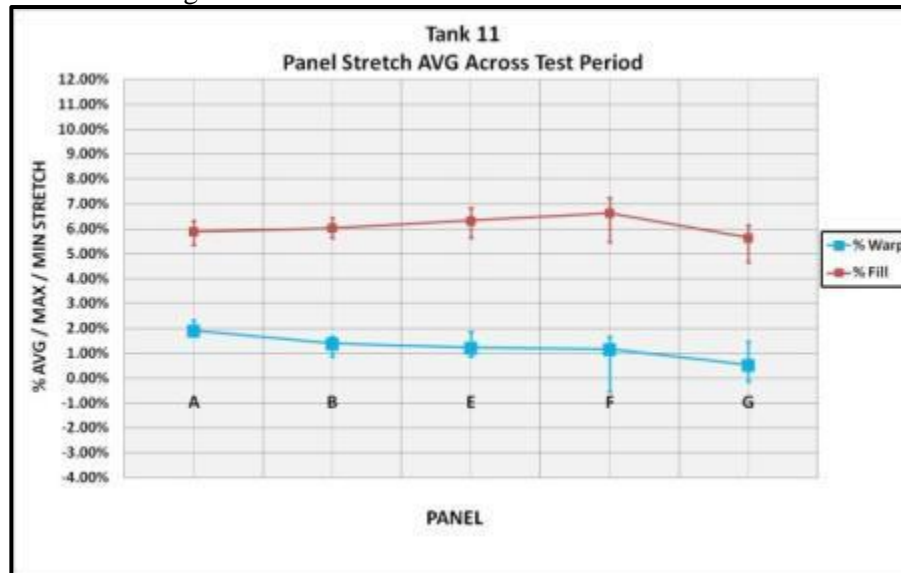
Tank 12S through Tank 23 are all considered variations of the standard (pillow) tank design. Tank 12S had a unique spiral design that made it markedly different from the other tanks; however, it still filled and took the characteristic appearance of a pillow tank. For all of the tanks in this series (12S – 23), both peak warp and fill stretch occurred consistently at the "D" panel location. The two panels located on a diagonal from the center vent toward a tank corner, panels "A" and "G", were typically associated with the next highest fill stretch. The lowest typical stretch was measured consistently at "F" which is located in a tank corner. This is contrary to some tank finite element analysis (FEA) models which suggest that the highest tank stresses occur in the corners. The next lowest encountered stretch was measured in panel "E", located just above the closing seam edge on the center of the warp panel where the highest stretch panel "D" is found. This is due to the close proximity of the closing seam where multiple plies of material welded together stiffen that area and reduce stretch. Panel "C" also shows reduces stretch. This is due to

its location directly adjacent to the manway / filler / discharge port and the associated doubler or tripler patch.

Although various seams were utilized across these tanks, they seemed to have little or no impact on tank stretch. There may have been a slight stretch reduction (approximately 1% or less) between tanks (Tanks 14, 15, 22, 23) which employed the double butt seam (DBS) as opposed to those with a shingle overlap (SO) or alternate overlap (AO) warp panel seam.

Figure 5.4.40 – Tank 12S Average Panel Stretch across Test Period

Figure 5.4.41 – Tank 13 Average Panel Stretch across Test Period
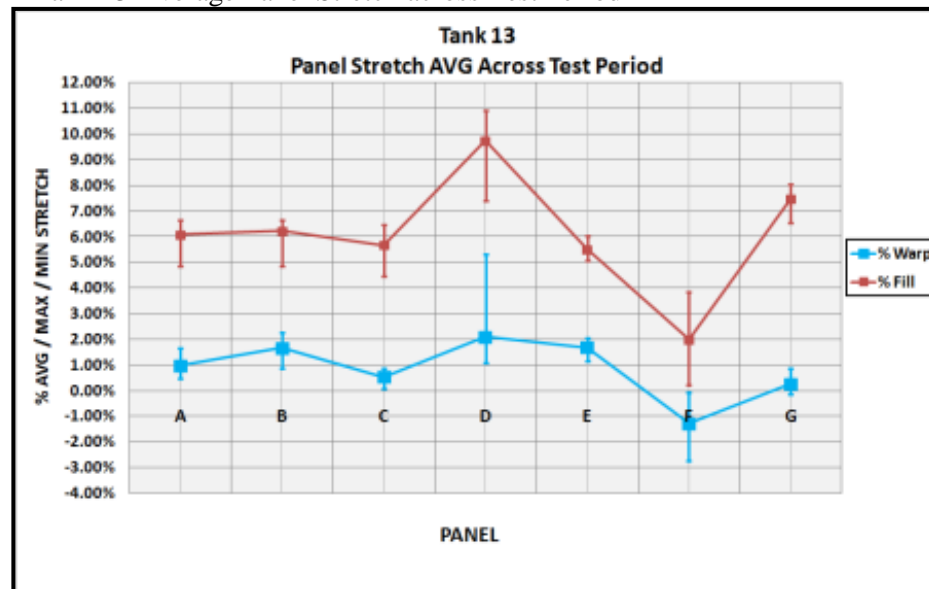
Figure 5.4.42 – Tank 10 Average Panel Stretch across Test Period
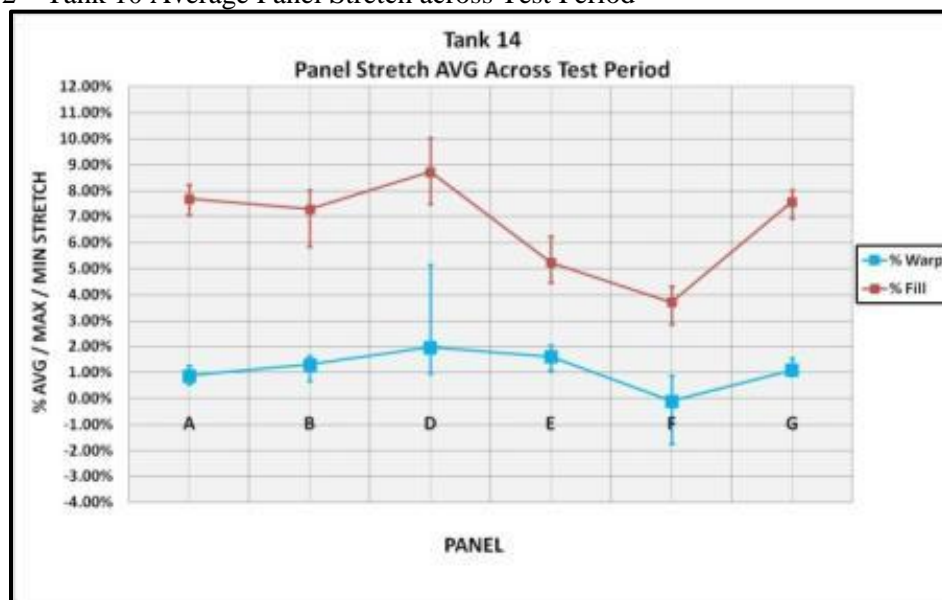
Figure 5.4.43– Tank 11 Average Panel Stretch across Test Period
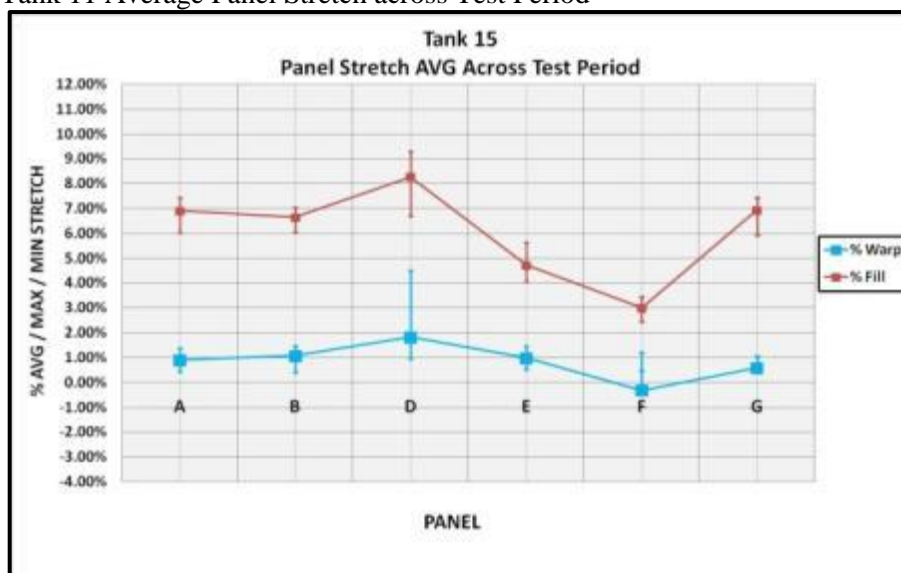
Figure 5.4.44 – Tank 16 Average Panel Stretch across Test Period
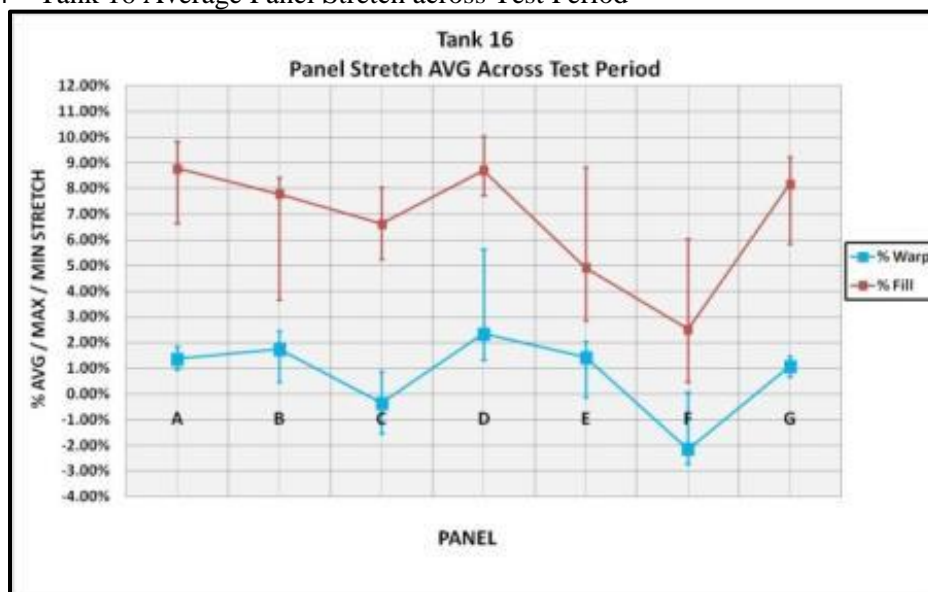
Figure 5.4.45– Tank 17 Average Panel Stretch across Test Period
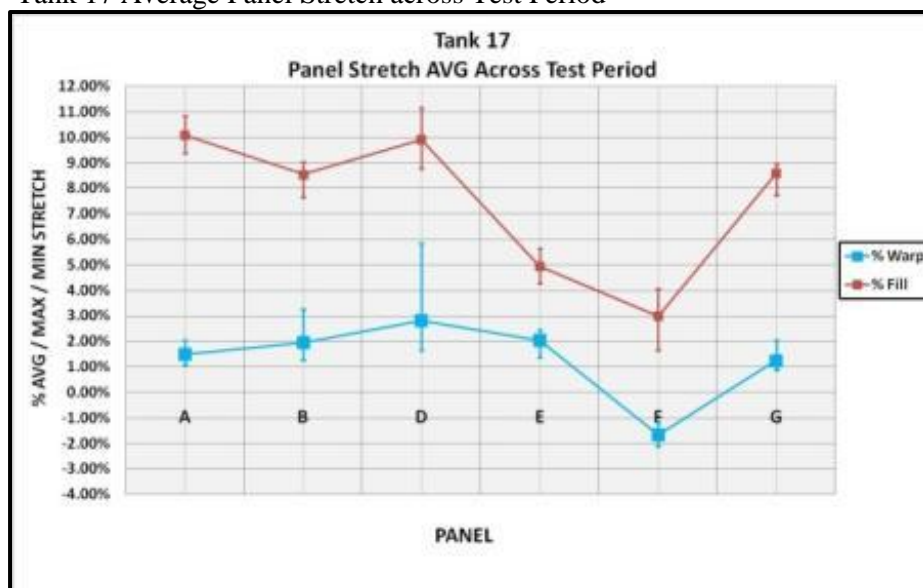
Figure 5.4.46 – Tank 18 Average Panel Stretch across Test Period
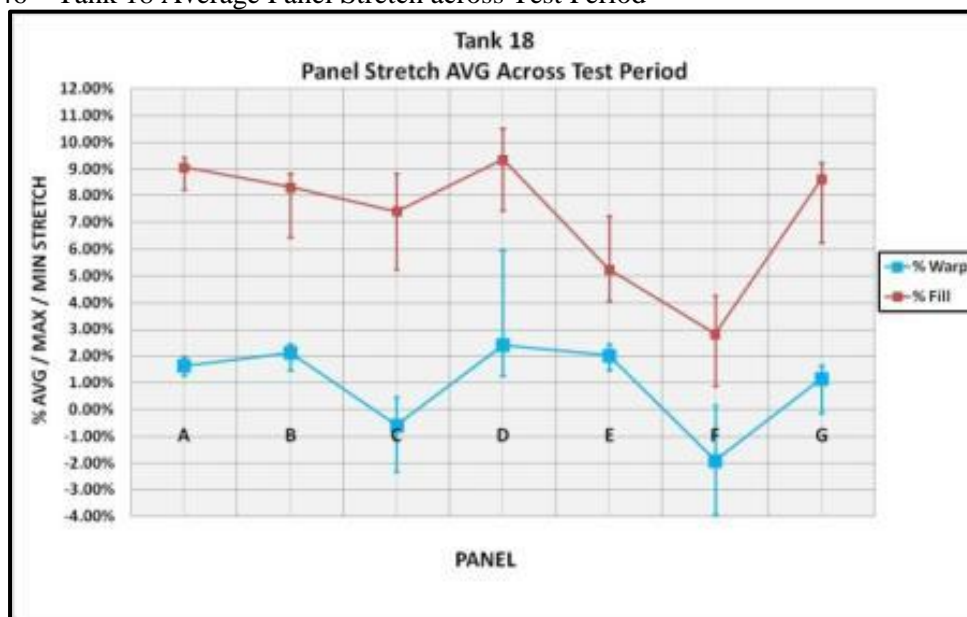
Figure 5.4.47– Tank 19 Average Panel Stretch across Test Period
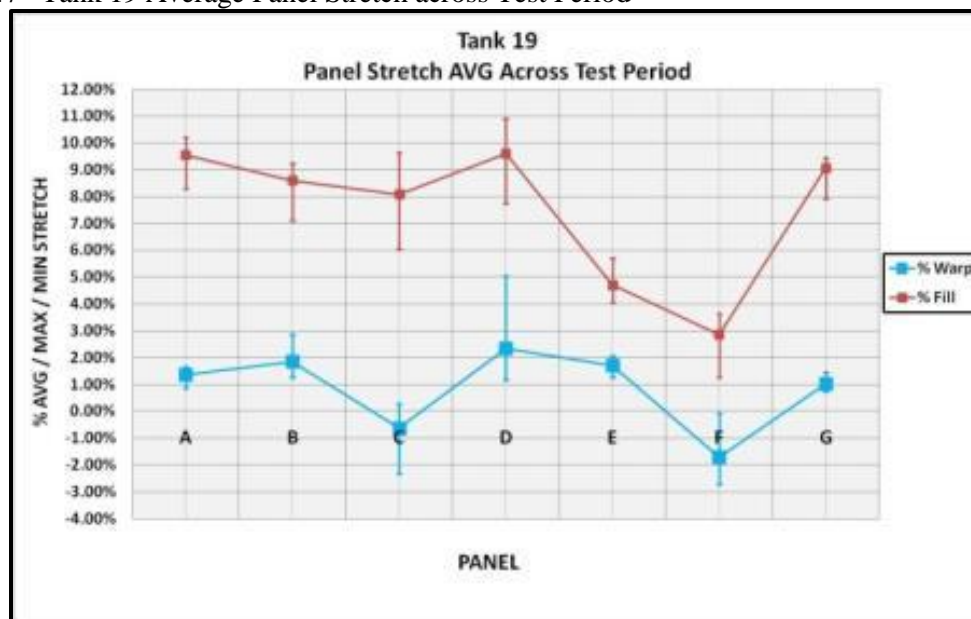
Figure 5.4.48 – Tank 20 Average Panel Stretch across Test Period
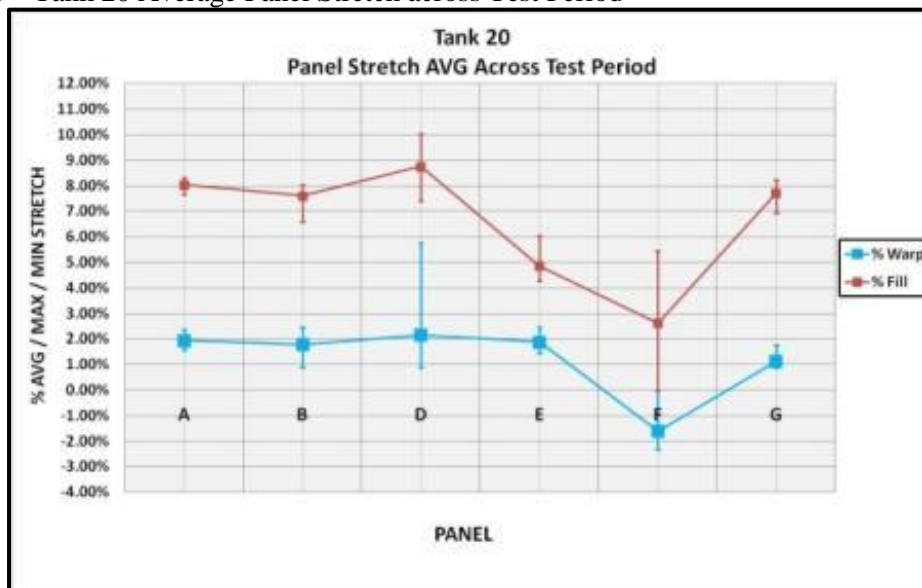
Figure 5.4.49– Tank 21 Average Panel Stretch across Test Period
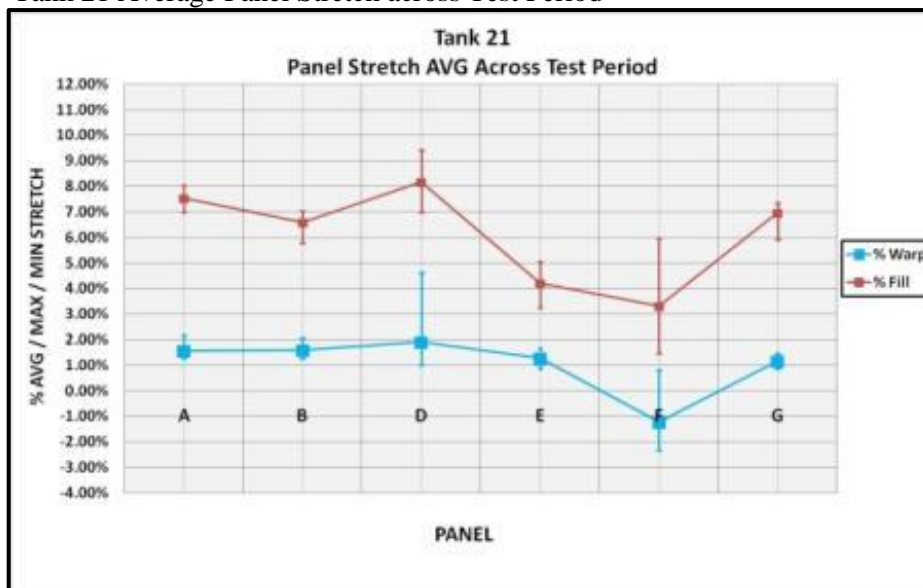
Figure 5.4.50 – Tank 22 Average Panel Stretch across Test Period
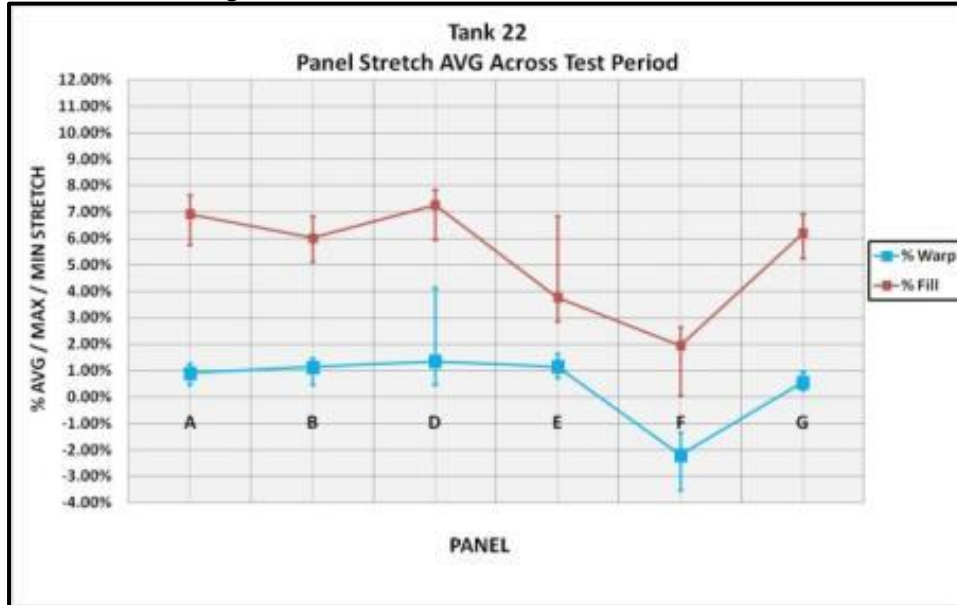
Figure 5.4.51 – Tank 23 Average Panel Stretch across Test Period
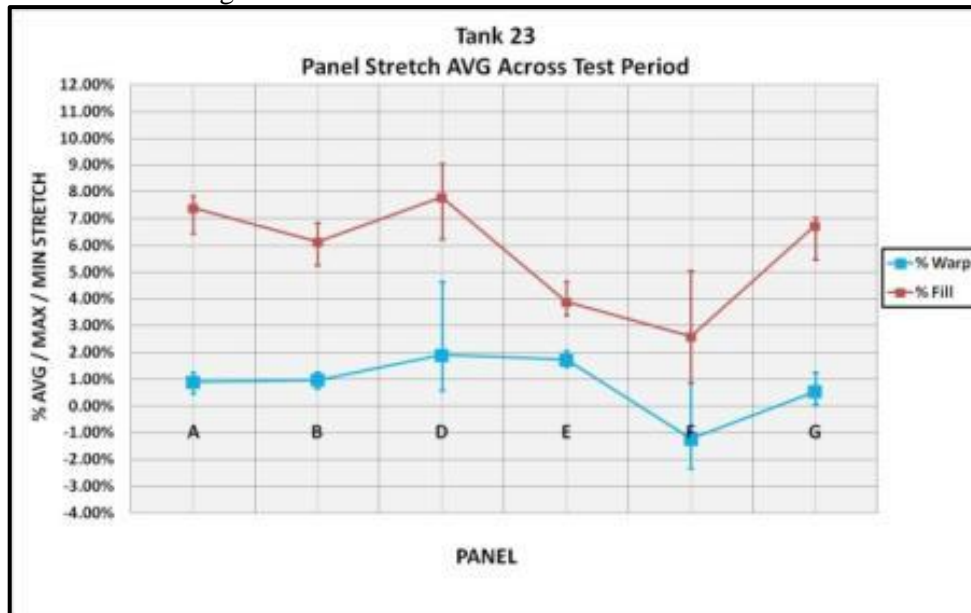
The prototype tanks showed consistently lower stretch at overfill. The worst case stretch location "D" did experience measurements that exceeded the >7.7% fill and >1.7% warp requirement represented by the standard deviation error bars. However, on average, these values were slightly lower than the target. Paired with the lower zero baseline stretch numbers seen in Figure 5.4.31, overall the prototype tank designs stretched less. These tanks were designed based on a 3,000-gallon three dimensional volume in which the tank material would have little or no significant stretch. The material in a standard pillow tank, by comparison, begins stretching at 50 − 67% of the total fill volume. Adding in the additional material and lower tank height per volume these designs require, the results are as expected.

Overall, since Tank 29 still is the prototype closest to a pillow tank in final design shape, its panel stretch reflects more consistently than those found in Tanks 12S – 23.

Figure 5.4.52 – Tank 24 Average Panel Stretch across Test Period
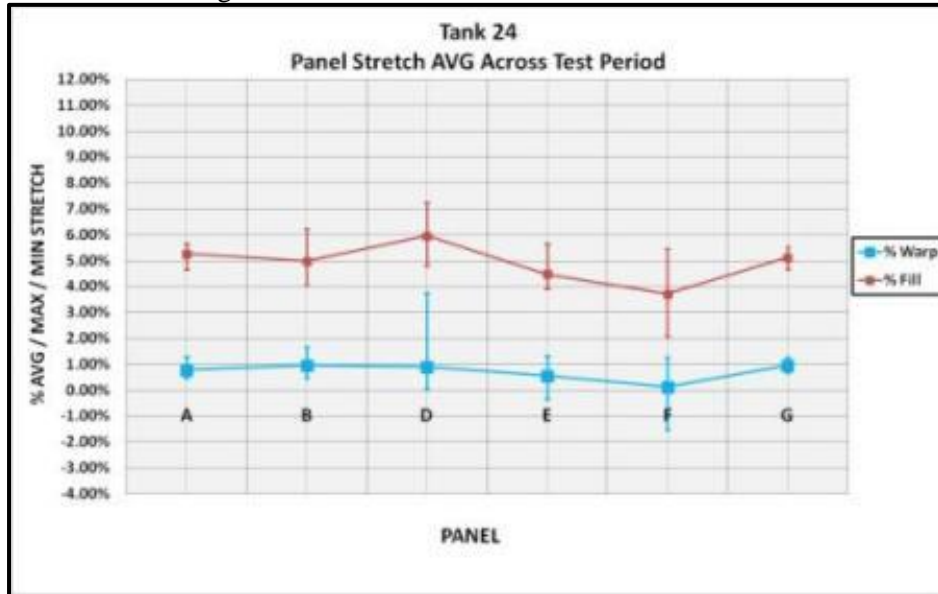
Figure 5.4.53 – Tank 25 Average Panel Stretch across Test Period
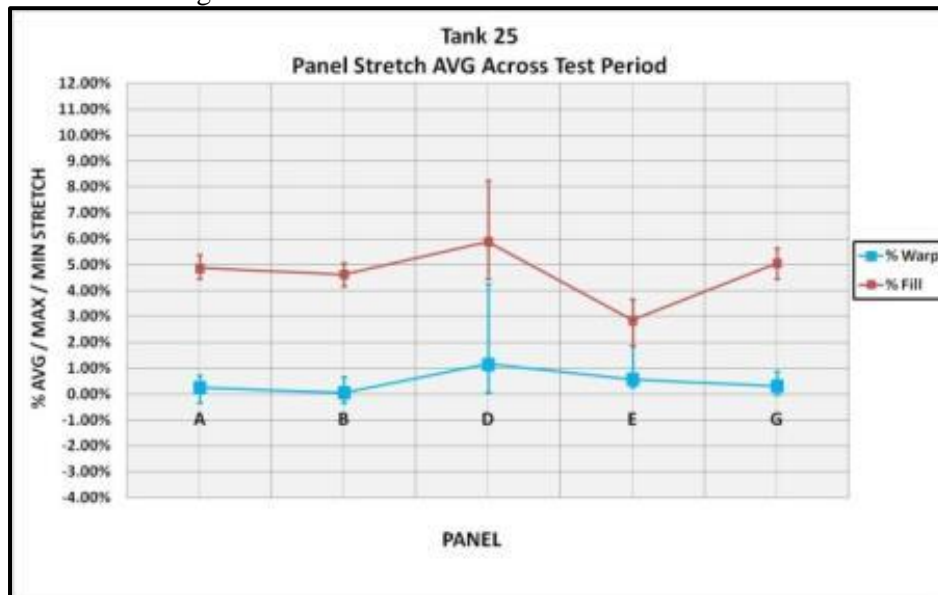
Figure 5.4.54 – Tank 26 Average Panel Stretch across Test Period
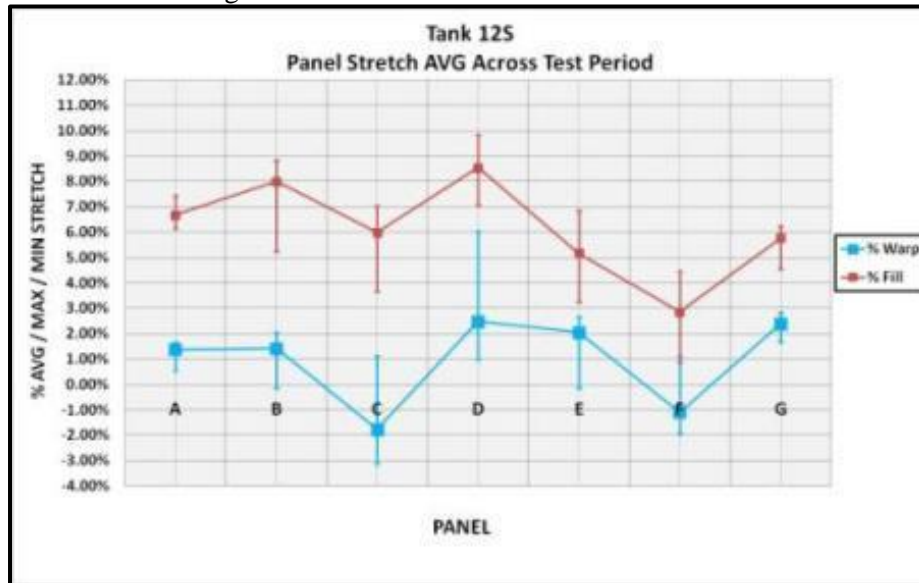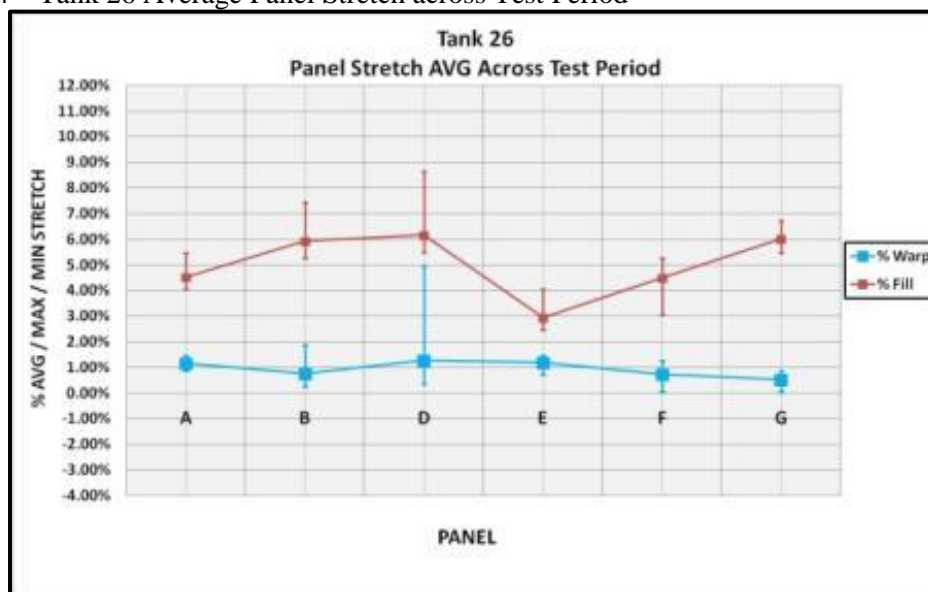

Figure 5.4.55 – Tank 27 Average Panel Stretch across Test Period
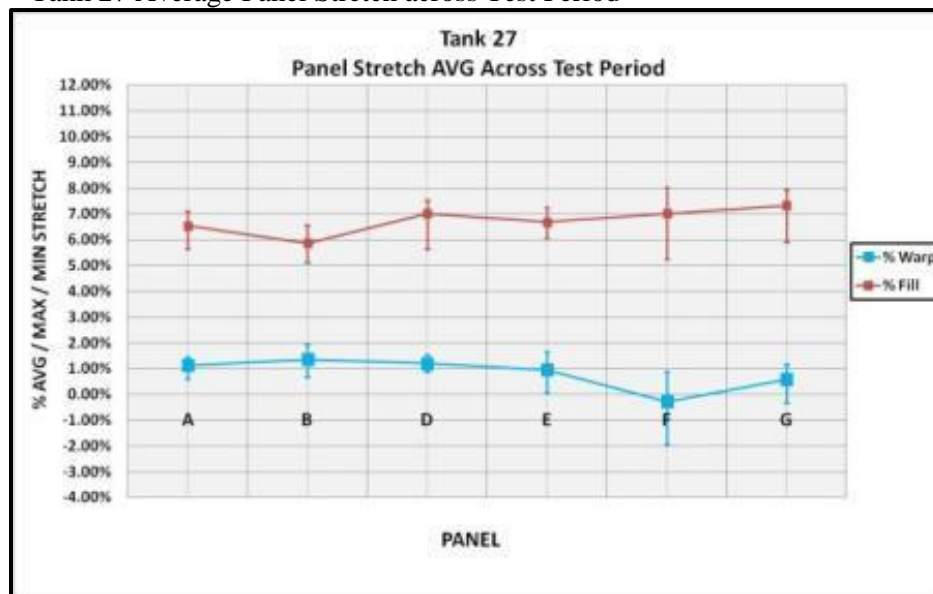
Figure 5.4.56 – Tank 28 Average Panel Stretch across Test Period
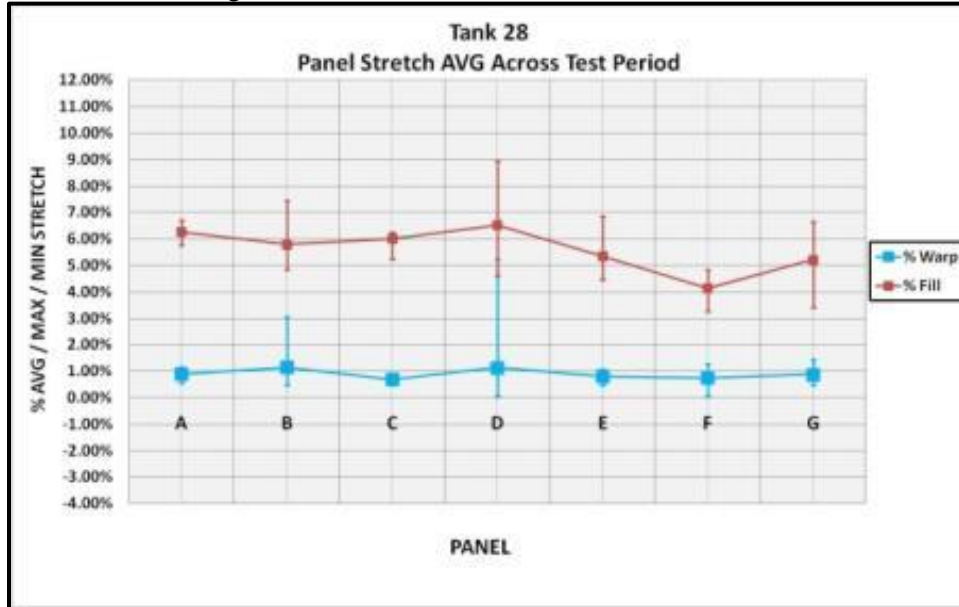
Figure 5.4.57– Tank 29 Average Panel Stretch across Test Period
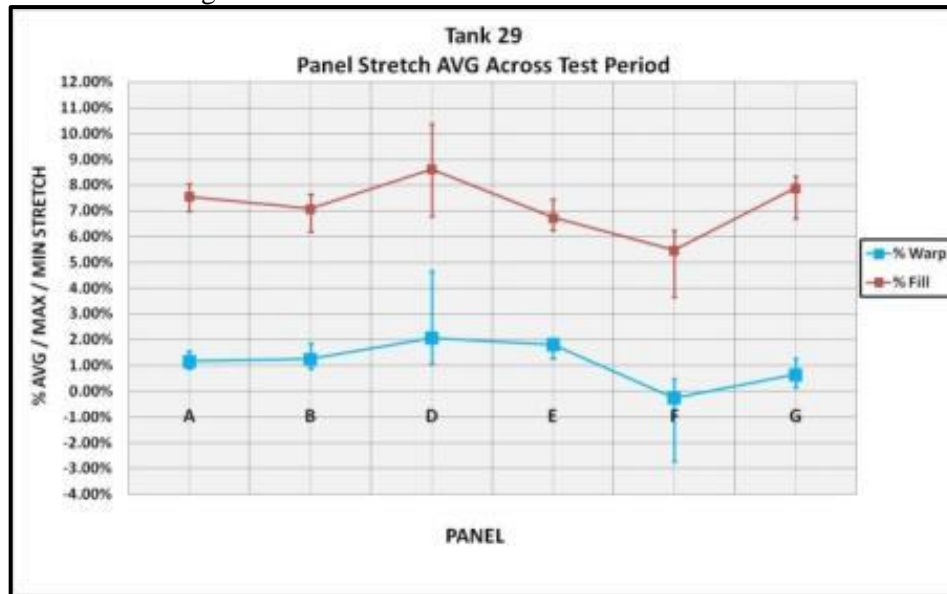
Hence, these graphs illustrate further evidence of the overall reduction of stretch between the pillow tank style of design and the prototypes.

In general, the fill and warp stretches both spiked during the first three to six months of the test, then they dampened and reached an equilibrium point throughout the remainder of the test. The anticipated increase in stretch during the second summer was not as evident as the first. Temperature accelerated tank stretch during the initial summer months because the initial tank fill (pressure) contributed more to the material stretch than temperature at least up to 105°F.

The contributing factors in reducing the stretch and the stress in the tank material include:
- the design of the tank,
- additional material in the prototype tanks (5-15%),
- prototype tank footprint fully supported by the ground with no fuel suspended (Section 4.2, Figure 4.2.8), and
- lower tank height.

The peak tank stretch encountered in the field was definitely worst case with all tanks exceeding the 7.7% fill and 1.7% warp threshold values. In some cases, these threshold stretch values were exceeded by 40% due to initial tank stretch and ambient temperature.

5.4.2   Temperature Measurements

5.4.2.1 Field Climatic Conditions

SwRI was chosen as the field test site due to its hot climate which would most closely model the current theatre of operations. It offered a broad range of temperature extremes with summers in excess of 100 °F and winters with occasional drops below freezing. Figure 5.4.58 summarizes the average monthly temperatures (blue bars) measured throughout the 18 months of field testing. High and low temperature extremes are noted by the red error bars. Testing started in JUN 2012 with average temperatures close to 85 °F and extremes exceeding 100 °F for the first 4 months. The highest temperature recorded was 108 °F in JUN 2013. During the winter cool down, temperatures averaged around 55°F with minimums as low as 29 °F with frost.

In addition to the temperature fluctuations, a few high wind events were noted. The peak high wind event occurred in FEB 2013 at 54 mph. Dust devils were noted as a common occurrence at or around the tank farm grounds. Daily data for the entire test period can be found in Appendix K.

Figure 5.4.58 – Average Monthly Temperatures with High and Low Extremes
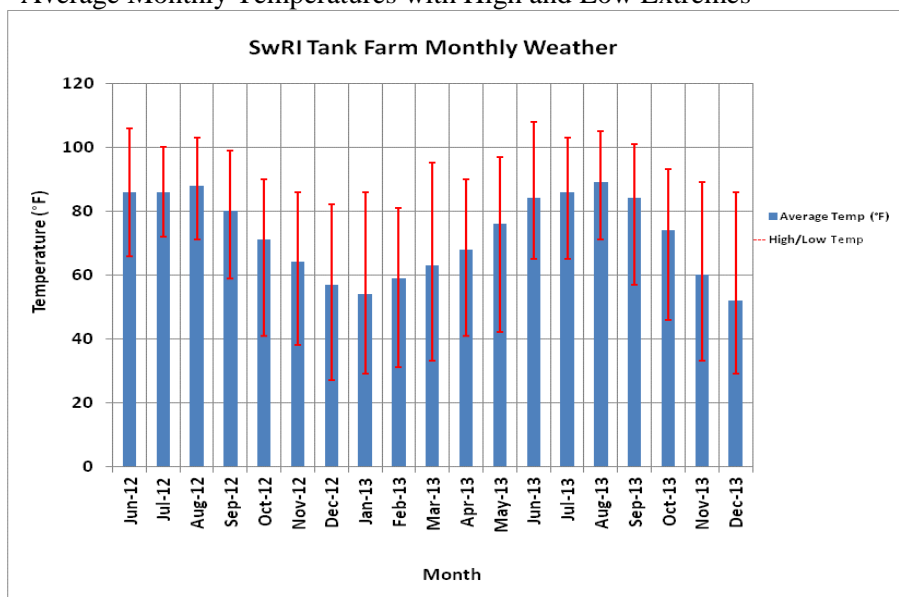
It was noted during testing that temperature did seem to have some impact on leak propagation, severity and rate. This is discussed in detail in the Leaks section (5.4.6).

5.4.2.2 Tank Skin Temperatures

External skin temperatures were recorded twice a week with an IR camera for each overfilled tank in an effort to verify a correlation between the tank skin and the ambient temperature. An example of such an IR scan is shown in Figure 5.4.59. On the tank body, the area within the rectangle is analyzed to get an average skin temperature value. In this case the temperature was approximately 101 °F. At the time the picture was taken, at 4:40 pm on 6 JUN 2012 the recorded ambient temperature was approximately 93 °F and rising. Hence, the differential between the skin and ambient was 8 °F. By comparison, the less reflective tank berm was approximately 125 °F or 33 °F hotter. The reflective nature of the Seaman 1940 PTFF will serve to keep the internal fuel temperature down. This material is designed to have a higher level of reflectance; minimizing heat absorption and reducing solar heat gain. The modification to the color standard 33446 by U.S. Army Tank Automotive Research, Development and Engineering Center provided the opportunity to address temperature of the tank. It is anticipated that it should be near the average daily temperature.

Figure 5.4.59 – IR Camera Average Area Scan – Tank approximately 101°F, Berm Foreground ~125°F
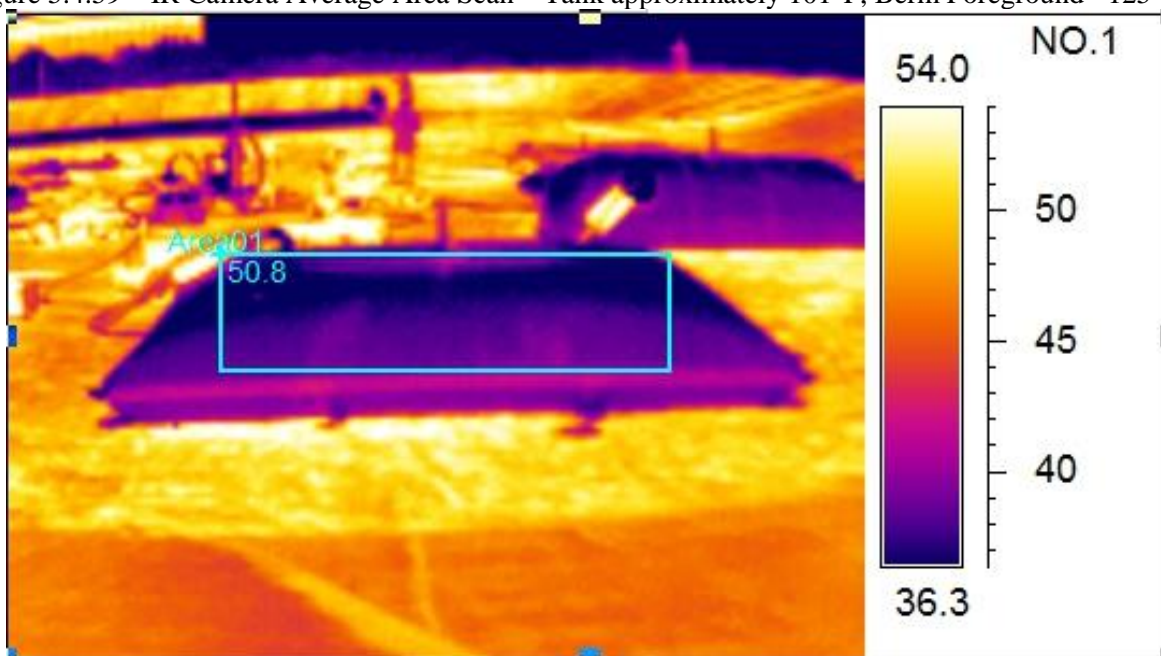
Checking the ambient temperature at the SwRI Weather Underground station against the time and date stamp of each IR scan taken, a correlation between External Tank Skin and Ambient Temperature could be derived. Figure 5.4.60 illustrates a typical temperature correlation. All of the remaining correlations can be found in Appendix U.

Figure 5.4.60 – Representative External Tank Skin / Ambient Temperature Correlation

IR Camera / Ambient Temperature Correlation

$$y = 0.8048x + 16.677$$
$$R^2 = 0.8891$$

Average Tank Temperature (°F) vs *Ambient Temperature (°F)*
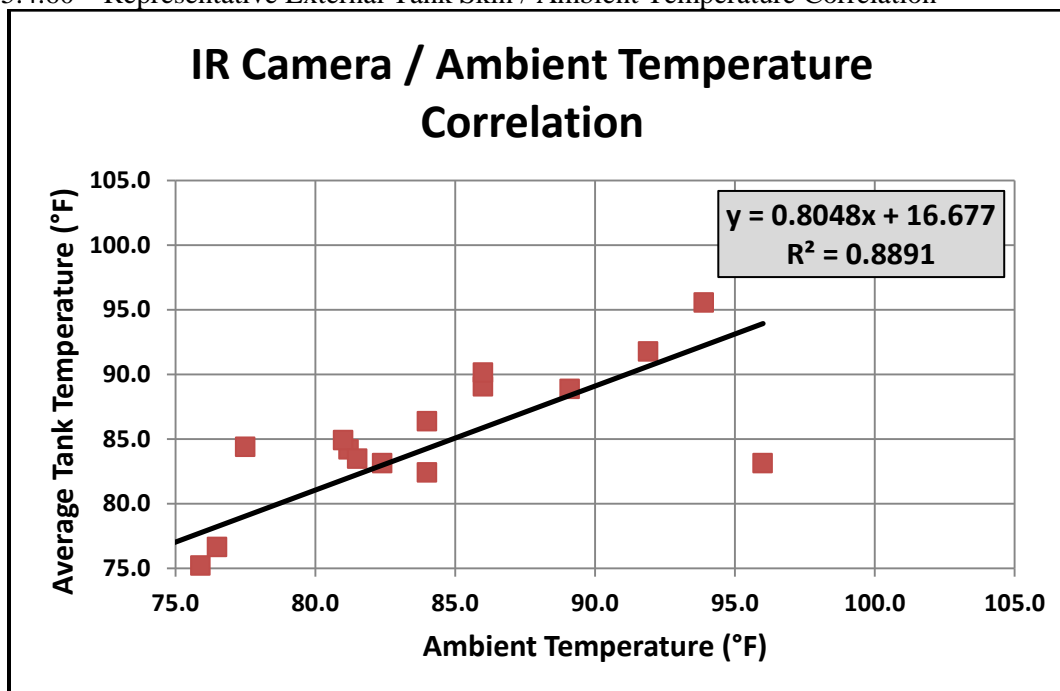
5.4.3   JP-8 Fuel Analysis

Since baseline data regarding long-term fuel storage in CFTs was not available, the alternative was to monitor the fuel quality to verify that it did not change substantially across the test period. The SwRI staff drew two fuel samples each quarter (one for each berm / bay) and a chemical assay was performed. The results of each assay per berm / bay are listed in Table 5.4.6. It covers the 5 quarters starting in SEP 2012. In addition, a final assay was performed on the fuel shuttled back into the 50K at the end of the test. No additional modifications to the fuel were made throughout the test period.

Table 5.4.6 – Fuel Sample Chemical Assay

Measured Property	Specification	Q4 2012 Fuel Assay		Q1 2013 Fuel Assay		Q2 2013 Fuel Assay		Q3 2013 Fuel Assay		Q4 2013 Fuel Assay		Final Fuel Assay
		Teen Berm	Twenty Berm	Teen Berm	Twenty Berm	Teen Berm	Twenty Berm	Teen Berm	Twenty Berm	Teen Berm	Twenty Berm	50K Tank
Density/API by Meter (15.5C/60F)	0.775 kg/L to 0.840 kg/L	0.7915	0.7911	0.7914	0.7924	0.7901	0.791	0.7905	0.7905	0.7904	0.7912	0.7908
(FSII) Fuel System Icing Inhibitor Content	0.15%	0.06	0.12	0.04	0.04	0.04	0.03	0.02	0.02	0.02	0.02	0.01
Electrical Conductivity	50 to 600 pS/m	190	220	176	166	259	230	202	192	208	219	190
Flash Point (Pensky-Martin)	38 C	51.5	50.5	50	50	49.5	49.5	50.5	50.5	45.5	45.5	46.5
Karl Fisher Water Content	<5 ppm	57	36	38	42	99	121	70	64	66	50	31

The fuel remained relatively stable throughout the 18-month test period, with slight reductions in density, FSII, flash point and a slight increase in water content.

5.4.4   Strapping Charts

For any lot of tanks for a given contract award, the fabricator must supply a strapping chart. The strapping chart is utilized in the field to determine tank volume as a function of tank height with the "stick and string" method (DESC Policy I-11 and I-29). After welding and air testing, a fabricator typically will create a strapping chart of tank height against water volume measured with a flow totalizer. For the

purposes of this study this was done at fixed increments (e.g., 500, 1000,.3000). In some instances, only the operational (100% fill - 3,000 gallons) and / or BRAG fill heights (70% fill - 2,100 gallons and 50% fill - 1,500) may be provided.

5.4.4.1 Fabricator Charts

For the purposes of this testing, one fabricator provided strapping chart information at every 500 gallons filled. The other fabricator supplied values for only the 3,000-gallon tanks and the maximum tank fill.

As mentioned previously, there were several concerns with the current method of measurement. These include:

      a.   Charts are created in a factory setting with cool filtered tap water in a somewhat regulated climate. The impact of climate on stretch and the strapping chart may not be fully realized during this process

      b.   The time for the tank to settle and equilibrate is limited when compared to the three to six months it took for the field tanks to stretch.

      c.   After the tank has reached full stretch in the field, filling to the strapping chart height may lead to filling in excess of the specification levels.

      d.   With an approximate average of 3 tons of mass per every 1,000 gallons of JP-8, tank and associated settling of the ground underneath will occur until reasonable soil compaction is reached.

5.4.4.2 Strapping Chart Curve Fitting

All fabricator strapping charts were plotted, 12 with 500 gallon increments and 8 with only the 3,000 gallon and maximum fill volume provided. To verify the volumetric fill of the tanks in the field, two volumetric totalizing meters were chosen. In the Teen Bay (Tanks 10-19), an Omega Turbine Flow Meter was installed. For the Twenty Bay (Tanks 20-29), a Sierra Vortex Mass Flow Meter was chosen. This was done to verify repeatability across more than one volume flow meter / totalizer.

To create a field strapping chart, it was necessary to start with as empty a tank as possible. The tanks did not have drains installed because doing so might create an unnecessarily hard to reach leak point. An effort was made to empty the tanks as much as possible with the shuttle pump. There was always a residual level of fuel left in the tank that could not be removed. This volume was added as a starting offset after confirming the residual fuel height at numerous points across the top face of the tank. At the end of the test period when the tanks were cut up for forensic evaluation, it was verified visually that the amount of fuel left in the tanks after the shuttle pump would run dry was close to the estimated (inches of fuel).

Three representative strapping charts have been included for review (Figures 5.4.61 – 5.4.63). All the remaining strapping charts are located in Appendix Q. Figure 5.4.61 represents data for Tank 21-1 and is an example of a test where 8 points were supplied by the fabricator for the original tank strapping chart. The original strapping chart data is **shown in blue**. A second order polynomial equation was used to fit the data with a resultant high coefficient of determination (R^2). For each curve the resultant equation color matches the line color. Based on the field volumetric flow totalizer measurement from JUL 2013, the **red polynomial curve and equation** were then generated.

Figure 5.4.61 – Fabricator / Field Test Multiple Point Strapping Chart Comparison
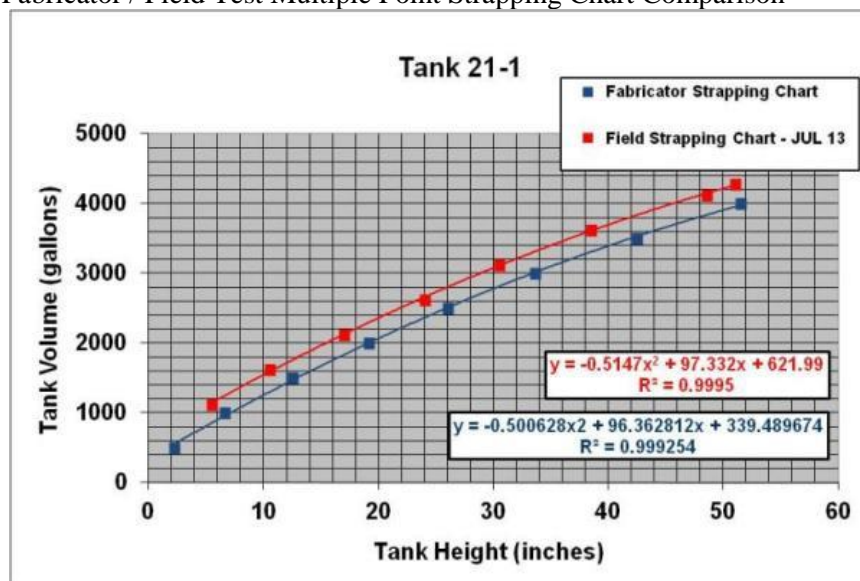
The process was repeated for all of the tanks including those in which the fabricator only provided a two-point, 3,000 gallon and maximum fill value. During the field test verification, multiple points were recorded to provide an adequate curve fit and representation of the impact of change in tank material stretch.

Figure 5.4.62 – Fabricator / Field Test Strapping Chart Comparison with Starting Two-Point Curve
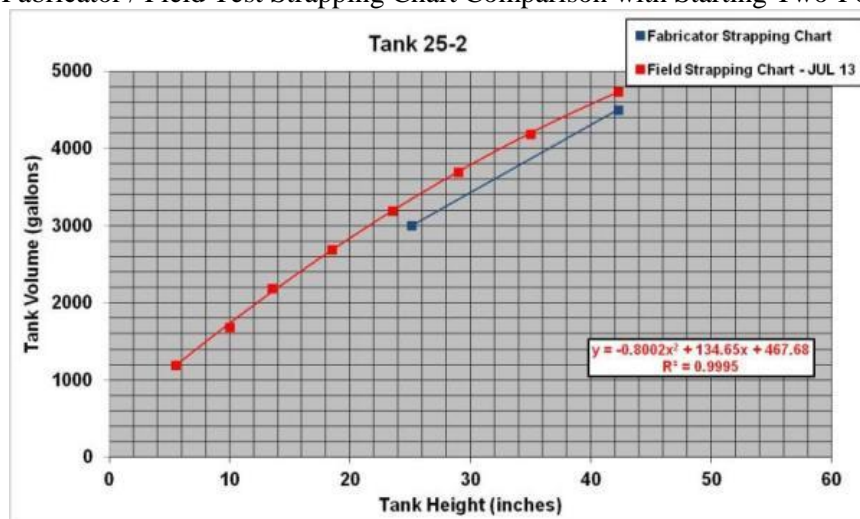
It was possible to run a second set of confirmation tests in the Teen Bay during early JAN 2014. An attempt was made to do the same in the Twenty Bay however there were some issues with the meter. The test program was ended January 2014 to allow adequate time for tank leak forensics and evaluation. Figure 5.4.63 is representative of the strapping charts (Tanks 10 – 19) where it was possible to add this third curve. The data for the third curve and equation (JAN 2014) is **shown in green**.

Figure 5.4.63 – Fabricator / Field Test Strapping Chart Comparison from with Omega TFM
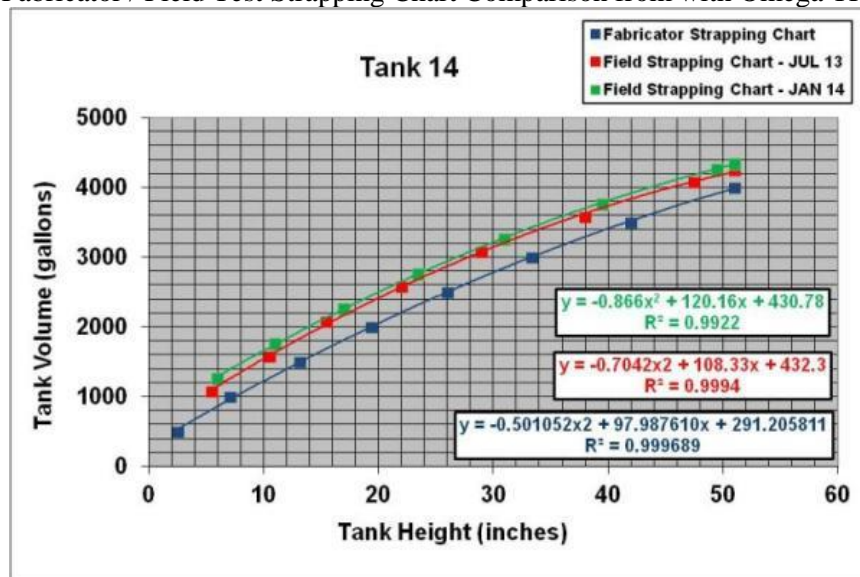
5.4.4.3 Field Strapping Chart Offset

Based on the field generated curves and equations, it was possible to determine the percent volume over target fill (3,000 gallons) encountered. This was calculated for each tank and a percent volume over target fill established in Table 5.4.4. The range was from 7.67% to 13.77% with an average value across all tanks of 10.79%. It is thought this is due to the tank materials stretching during its first 3-6 months of over-filling (examples are shown in Figures 5.4.32 to 5.4.37). The tanks were always filled by the primary height standard, per the fabricator strapping chart. After the material took a stretch offset (zero fill baseline – Figure 5.4.31), the tank would hold more fuel if filled to the same height. If the tank specification allows for a maximum overfill of 10% at a target volume of 100% (in this case 3,000 gallons), filling to the height designated on the fabrication strapping chart may approach or exceed that limit. This is contingent on a number of factors including tank location and ambient temperature. As shown in this study, due to the safety factor engineered into the material, the tank maintained its integrity without any major failures even when filled to 150% of capacity.

Table 5.4.4 – Field Strapping Chart Overfill

Tank #	Field Strapping Chart Volume (gallons)	% Over Target Fill
T10	3244	8.13%
T11	3288	9.60%
T12S	3334	11.13%
T13	3397	13.23%
T14	3263	8.77%
T15	3364	12.13%
T16	3286	9.53%
T17	3384	12.80%
T18	3230	7.67%
T19	3397	13.23%
T20	3270	9.00%
T21	3413	13.77%
T22	3236	7.87%
T23	3300	10.00%
T24	3382	12.73%
T25	3346	11.53%
T26	3352	11.73%
T27	3379	12.63%
T28	3326	10.87%
T29	3283	9.43%
Average % Over Target →		**10.79%**

In an effort to verify this theory, the approach taken in the model tank study was utilized to check stretch in both warp and fill directions. Warp and fill side views of two different tanks were selected. The images were chosen based on the cameras centralized perspective relative to the horizontal and vertical long axis of the tank. Pictures from JUN 2012 and JAN 2014 were compared and analyzed to scale as imported images in AutoCAD. Tank 24 was selected for the warp and Tank 27 for the fill comparison. Once a spline was generated around the perimeter of the tank, the JUN 2012 and JAN 2104 images could be compared to determine the average overall stretch. The perimeter stretch analysis for the warp view revealed an increase of 1.2% (Figure 5.4.64) while the fill view value was 5% (Figure 5.4.65).

Figure 5.4.64 – Tank 24 Warp View Comparisons between **JUN 2012** and **JAN 2014**
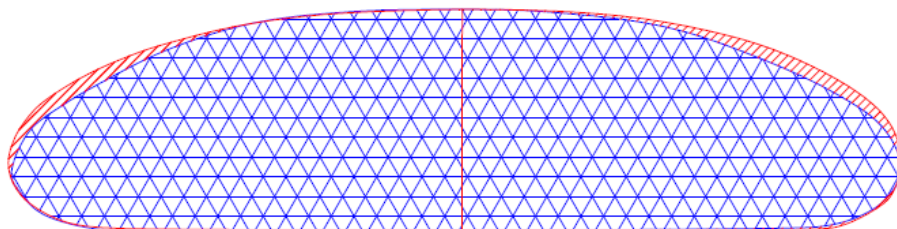
Figure 5.4.65 – Tank 27 Fill View Comparisons between **JUN 2012** and **JAN 2014**
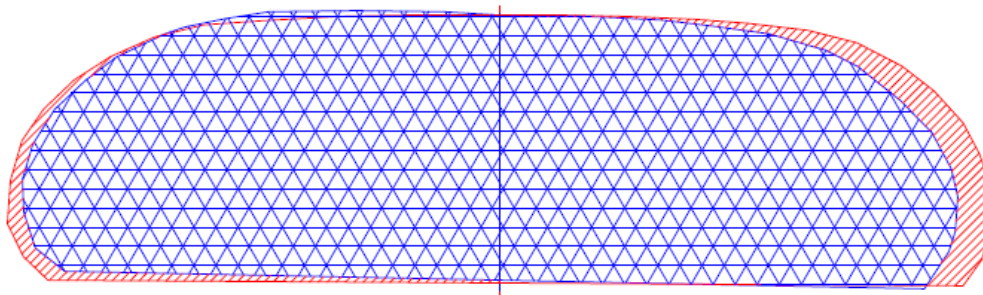
Hence, this method served to verify, to an extent, the strapping chart results (i.e., that the tank material stretch is leading to change in tank volume per the prescribed strapping chart height). It is not possible with the photographic image, however, to account for any fuel which has settled in depressions and pockets in the bottom of the tank due to soil compaction. This could also definitely have an impact on tank volume measurement since the fabricators strapping chart is typically created on a non-compacting solid plant floor. A reference regarding the issue of soil compaction under load is Huong, TC et al., "Two-Dimensional Analysis of Water-Filled Geomembrane Tubes Used as Temporary Flood-Fighting Device", February, 2001.

Additional inspection of the comparative images showed a steeper shoulder from the vent toward the tank end upon initial fill that eventually flattens out over time. This was consistent with the panel stretch as a function of test period (Figures 5.4.32 – 5.4.37) where the "D" panel (top center of tank) peaks initially and then reduces while some outer panels increase slightly in stretch.

After the first year of field testing, it was determined that it may be possible to get a better understanding of the contribution of temperature versus initial fill stretch on expanding tank volume. A proposal for an extension to the original study was submitted to get this testing done. However, the extension was not approved so it was not possible to reach any additional conclusions.

5.4.5   Tank Footprints

Originally it was thought that the tanks' footprint might be a good way of gauging the change in the tank as it was filled to target (100%) and overfilled (maximum or 150%). Over the course of the test period it was found however that this method of measurement was not consistent and prone to human error due to the differences in tank designs and how the measurement method could be interpreted. The initial measurements were made within the same week by the same staff and were the most consistent. Subsequent measurements were made as time permitted by different groups.

A good example of some of the inherent variability in this method is the filling of any pillow tank design (Tanks 13 – 23). As the tank is filled, the corners remain the furthest out while the center on each edge is pulled in forming a horizontal concave profile. So measuring the corners is not truly representative of the tanks volume since the center axis may be 1-2 feet narrower than the measurement from corner to corner.

Based on the original measurements, a graph of the warp in Figure 5.4.66) and the fill stretch (Figure 5.4.67) are both shown. Each graph includes the 3,000-gallon – 100% target volume fill as well as the over-fill (OF) maximum or 4,500 gallon footprints.

Figure 5.4.66 – Warp Direction Footprints
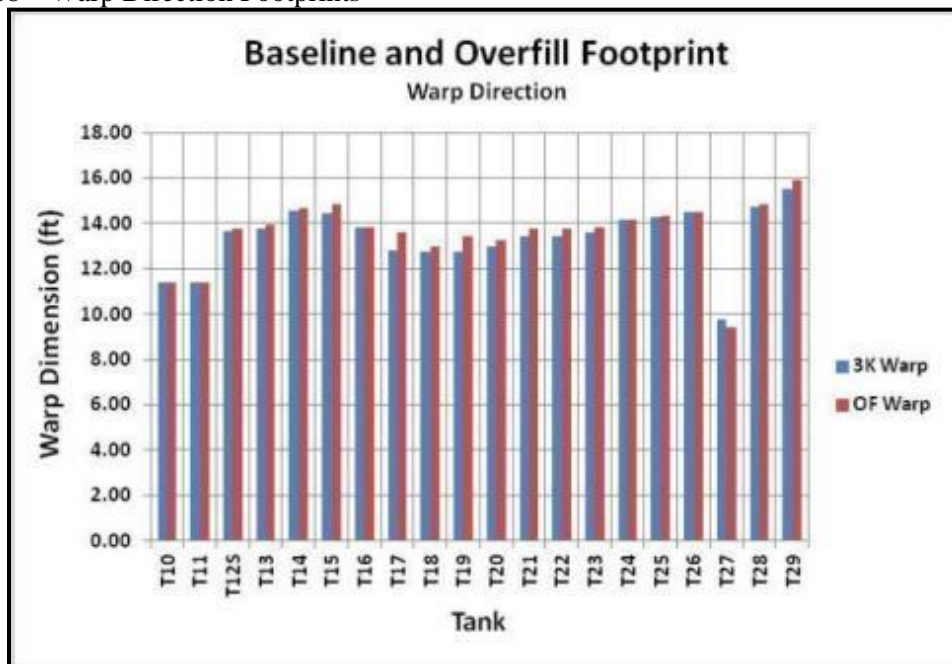
Figure 5.4.67 – Fill Direction Footprints
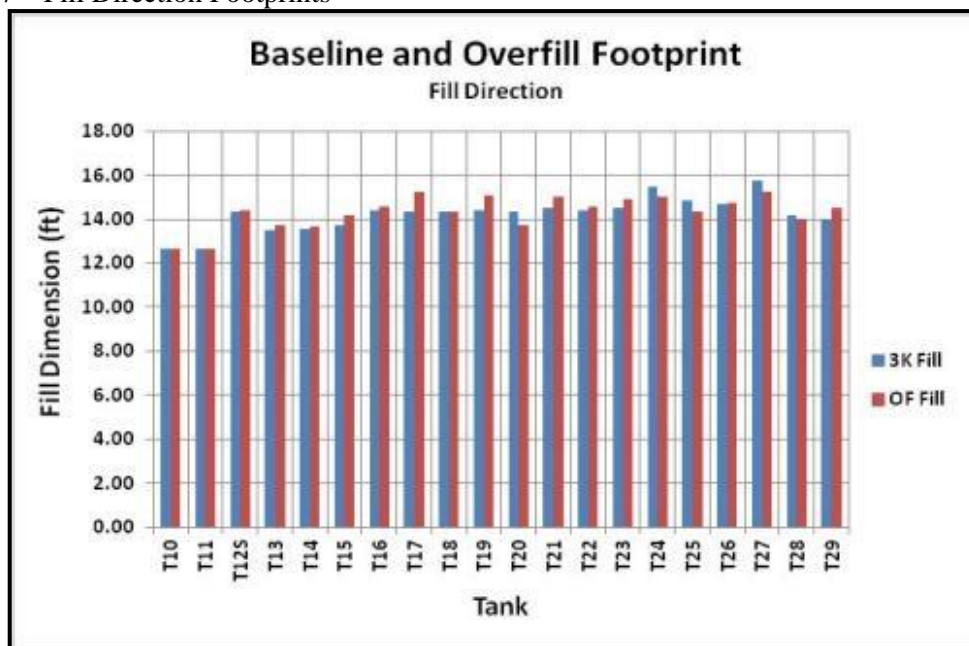
Further measurements were taken, however the variability caused by the method, the tank geometries, human interpretation and error lead to erroneous results.

5.4.6   Leaks

The purpose of this study was to overfill the 3,000-gallon experimental tanks to a level where the stretch reached or exceeded the field verified 50,000-gallon tank measurement (Figure 5.3.7). Due to variables such as material stretch and extreme temperatures, the peak stretch target was exceeded in some cases by up to 40%. This resulted in a true worst case study with a greatly increased potential for leaks.

A detailed discussion of potential leak root causes was covered in the FTA / FMEA sections. They may be traced to one or more causes:

- Tank Fabrication
- Material Manufacturing
- Field Environment and Events
- Field Handling
- Shipping
- Storage

5.4.6.1 BRAG Rating System and Testing Classification

For the purposes of this study, a modified version of the BRAG, TB 10-5430-253-13 - TECHNICAL BULLETIN FOR COLLAPSIBLE FABRIC FUEL TANKS (Department of the Army), was reviewed and approved by the program sponsor. The modifications dealt with the expanding the number of tank features analyzed to reflect the additional design variations across the tanks tested.

Table 5.4.5 – BRAG Standard and BRAG Modifications for Study

BRAG TB 10-5430-253-13	BRAG Modifications
Panels	Panels
Seams	Seams - WPS - Closing Seams - T-Seams
Blisters / Separation	Blisters / Separation
Seam Separation	Seam Separation
Fittings	Fittings Fitting Seams
	Corners
	Seam Tape

The leak rate classifications in the BRAG document were used as stated for grading the severity of the leak.

- CLI –Seepage of fluid (as indicated by wetness or discoloration) not great enough to flow. (Wet Spots)
- CLII – Leakage of fluid (as indicated by wetness) great enough   when wiped dry to reappear and flow in 30 seconds. Flow is not great enough to form puddle on ground.
- CLIII – Leakage of fluid great enough to flow from the tank and form a puddle of fuel on the ground.

5.4.6.2 – Leak Results Summary

The total number of leaks logged across 21 tanks tested through a period of 18 months was 282.

- 95.7% leaks were Class I (270/282)
- 3.9% leaks were Class II (11/282)
- 0.4% leaks were Class III (1/282)
  - Leak which caused original Tank 16 to be removed from service

Leaks were further differentiated between field, manufactured and fabricated related sources based on forensic inspection of leak samples extracted at the end of the study. A fabrication-related leak was assigned based on a number of criteria. These included leak appearance relative to first time filled, repeatable fabrication issues (e.g., repairs, slinky tunneling on closing seams) and root causes verified through forensic analysis. A few leaks were designated as possibly fabric manufacturing related, however, chemical analysis and further tests would have been required to verify this to determine whether the cause was due to contamination during the coating process or from an external field source. If a contaminant is present in the compound it may be possible to perform a chemical analysis, such as extraction or FTIR, to determine its chemical make-up. This assumes that enough contaminant is present for such an analysis and that a matching reference is available in the compound reference library.

- 154/282 = 54.6% were designated as fabrication related
- 5/282 = 1.8% were designated as potentially fabric manufacturing related

Adding to the number of leaks was the novel design of 16 of the 20 tanks. The two fabricators who committed to making these tanks needed to enlist welding methods which previously had limited use or had not been undertaken by their operations. Steps and precautions were taken to verify the integrity of their work. Steps were also taken to verify that they followed the process and quality control recommendations from the FY2008 study and appropriate MIL specification guidelines. A number of the prototype designs required unique extreme material handling considerations.

- 57 leaks on 6 Tanks (Tanks 10-15, fabricator design based tanks)
  - 20.2% or 9.5 leaks per tank
- 159 leaks on 9 Tanks (Tanks 16-23, FY2008 style tanks)
  - 56.4% or 17.7 leaks per tank
- 66 leaks on 6 tanks (Tanks 24-29, Seaman prototype tanks)
  - 23.4% or 11 leaks per tank

Hence, the FY2008 and prototype tank designs had higher rates of leak occurrence. The major contributing factors were:

- Use of RF welding on multiple-ply seams driven by tank designs; especially closing seams and corners,
- Corner clamp designs used on the FY2008 prototypes were problematic,
- Prototype seam tape adherence on curved surfaces, and
- Working with novel design and geometry considerations.

The leaks were tracked daily to gauge the impact of changing climatic conditions and overall tank performance. Testing was initiated early in JUN 2012 and continued through to DEC 2013. Overall tracking over the test period is captured in the Monthly Leak Pareto shown in Figure 5.4.68. During the summer months as ambient temperatures increased, the number of leaks appearing and the rate of fuel flow from each leak also increased. This leak appearance rate was highest during the first six months of operation, which coincided with the time of peak tank stretch measurement (approximately 22/month). As the ambient temperature went down during the winter months, both the number of leaks appearing and the rate of flow from each decreased (approximately 3/month). During the final six months of operation (JUN – DEC 2013), the leak appearance rate returned to 22 / month.

Figure 5.4.68 – Monthly Leak Pareto Highlighting Seasonal Leak Dependency
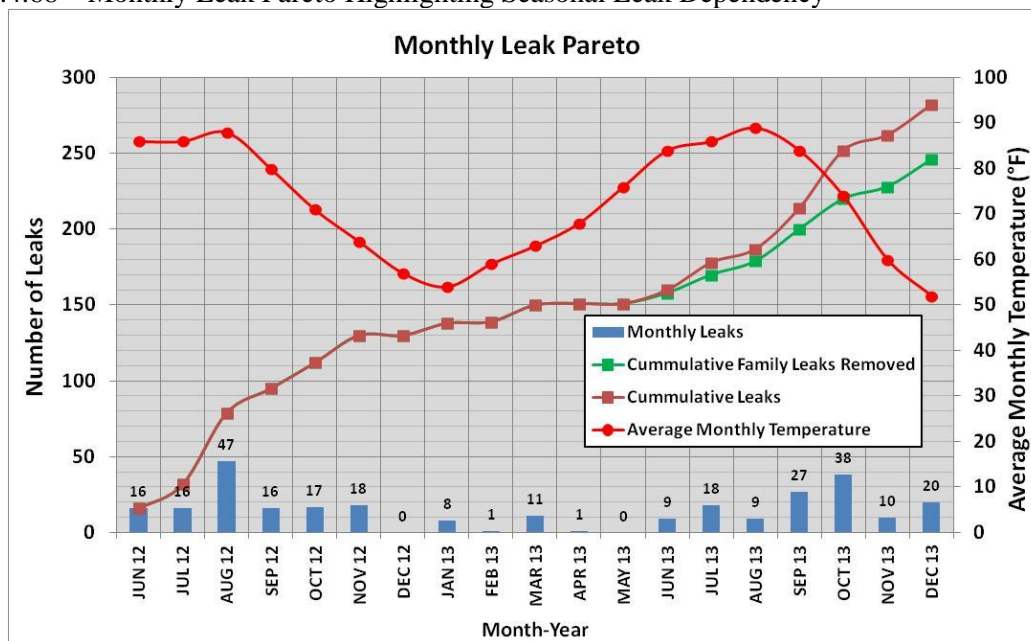
After close review of the new leaks, it was determined that a number of them, starting in May 2013 were all along the same seam and were propagating down from the top of the tank along the seam tape. From this finding, it was determined that a number of the leaks had a high probability of a single leak source. Reducing the leak number to remove the redundant leaks was then plotted as the **green line**. This resulted in a net reduction of 36 leaks to an adjusted leak rate of 16 / month.

5.4.6.3 Leaks by BRAG Feature

The leaks were categorized by BRAG rating to determine the major leak cause per each design feature evaluated. The results of this analysis are shown in Figure 5.4.69. This is broken down by field based leaks and tank fabrication attributed leaks per the discussion in Section 5.4.6.2. Of the fabrication related failures, 90/154 = 58.4% of the total were either closing seam or corner based. This is due primarily to the closing seam and corner designs employed in the 16 novel tank designs. Enough material was shipped to the fabricators who made practice tanks prior to starting on the tanks for testing. There is an associated learning curve that is tank design-based even when fabricating with familiar material. This illustrates the critical nature of having fully-qualified, experienced fabricators enlisted in large tank contracts and why start-up operations may sacrifice product quality.

The biggest issue relative to the fittings was the number of manways shipped without being fully torqued down. This was rectified in the field once the issue was recognized. In this case, many bolts had either worked their way loose in transport or were not re-torqued to specification after they were removed for drying out the tank after water testing.

Fitting seam leaks were attributed to either a lack of proper adhesion to the tank body or open, uncoated scrim within the manway.

Prototype seam tapes proved to be somewhat problematic. During initial evaluation, adherence of the seam tape at the tank weld was checked on straight welded runs. However, trying to apply the prototype tape, especially around curved or radius welds proved challenging.

Figure 5.4.69 – Total Leaks by BRAG Feature
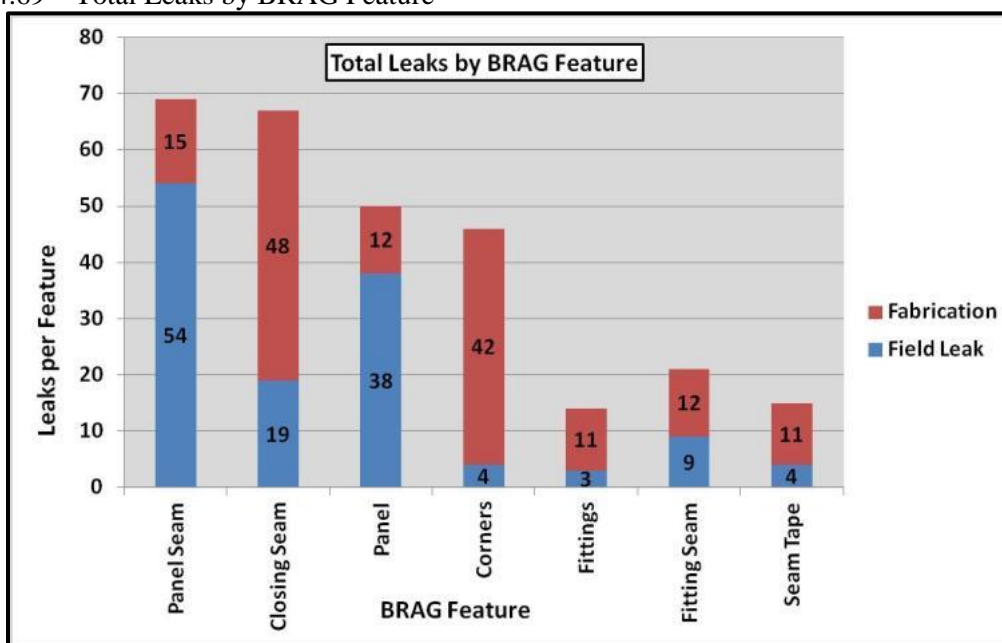
5.4.6.4 Leaks by Design Feature

Figure 5.4.70 drills down deeper into tank designs and the different types of design feature associated with each BRAG category. For each tank design type, there is a different base color. Tanks 10-15, considered to be fabricator typical designs, are **blue** or light blue. Tanks 16-23, design variations based on the FY2008 pillow tank design, are **red** or pink. The prototypes, Tanks 24-29, are either **green** or a **light green.** The darker color for each tank class represents leak attributed to the field operation or other event based cause. The lighter color designates leaks that are attributed to tank fabrication.

Figure 5.4.70 – Leaks Based on Tank Design and BRAG Category Feature
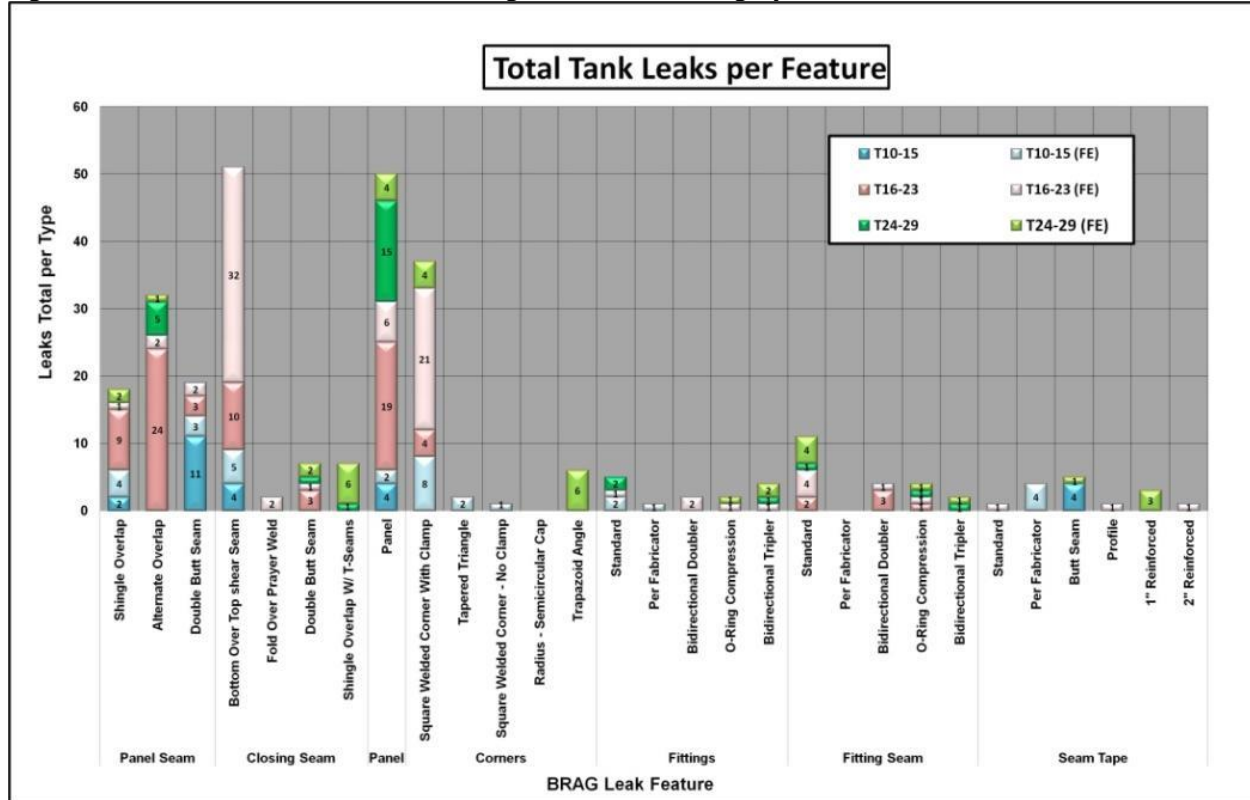
As anticipated, warp, closing seams and corners contributed substantially to the leak total. For the closing seams, evidence indicates that the Bottom Over Top Shear Seam (BOTSS) issues were mostly due to the combination of radio frequency welding with a slinky bar. Typically the seam was hit multiple times, especially in areas of weld overlap, which in turn caused too much compound flow and ridging or tunneling if the fabric in the seam. Examples of this are highlighted in the next Section 5.4.6.5, Tank Leak Forensics.

Although the double butt seams were also RF welded, they were less prone to leak. For the DBS, a standard welding bar was utilized instead of a slinky bar. There was very little evidence of too much compound flow, except perhaps on the very end of a seam near a corner. In a few cases, the DBS RF seam may have been slightly under-welded, as indicated by the number of cold welds (IUS) in the dead load testing.

The number of alternate overlap (AO) panel leaks was somewhat unexpected when compared to the shingle overlap (SO) and the double butt seam (DBS). However, some of this can be attributed to the use of prototype seam tape on 75% of the tanks with the AO panels as compared to 63% with the shingle overlap (SO).

Fitting and fitting seam leaks strongly indicated: 1) the need to verify the tank fitting torque specification once deployed and 2) the need for a sealant or an O-Ring Compression style of design to block the path of fuel in to the otherwise exposed scrim. The fabricators standard designs performed well.

5.4.6.5 Tank Leak Forensics

Upon completion of the test period, the 21 tanks tested were cut up based on the leak locations and the samples were shipped back to Seaman Corporation for further analysis. This analysis took one of two forms, 1) visual inspection to determine if the fault was macro in nature or, 2) sectioning around the area of interest and inspection with a microscopic camera.

The pictorial results that follow are presented by BRAG leak class with the major leaks (Class III and Class II) highlighted and a few selected Class I leaks of interest covered. After the micro section (Figures 5.4.71 to 5.4.100), the macro photographs cover additional observed leak origins.

The photographs are presented in sets with a leak location picture as well as the associated micro or macro descriptive shot. For each leak highlighted the BRAG Class, Tank # and Leak # identifier, BRAG feature type, date of leak and the likely cause is stated. For each BRAG Class, the tanks are presented in numerical order.

Figure 5.4.71 – Class III – T16-15 – Panel – 15 JAN 13
This was the only Class III leak observed. It is uncertain what caused the puncture. Fiber orientation indicated an outward-in directionality to the puncture. Massive compound and fiber damage can be seen. One possible explanation is that tank handling or a high wind event when the tank was empty could have lifted the corner clamp and the exposed bolt edges over onto the panel. This exact wind scenario was witnessed during the week of tank harvesting.
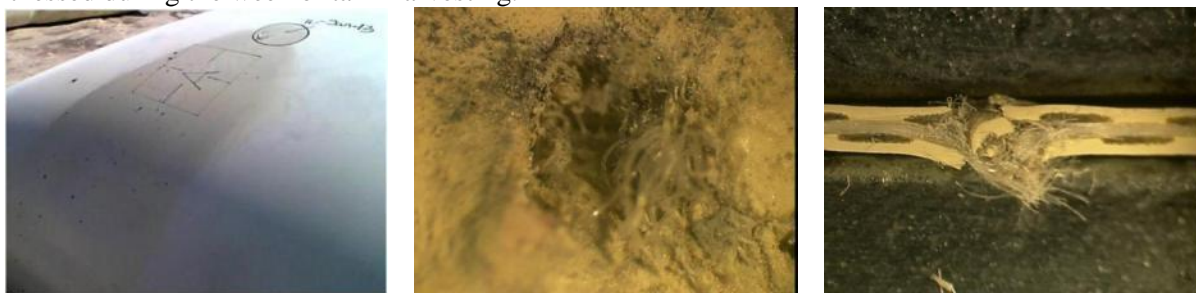
Figure 5.4.72 – Class II – T11-1 – Closing Seam – 23 JUL 12
This leak proved atypical. There was no evident fiber disruption, just compond surface cracking. However, it lead to a slower Class II leak with an onset within two months of being filled. It is not certain if the cracking is due to localized stress or the use of a chemical agent for surface preparation prior to welding.

Figure 5.4.73 – Class II – T11-2 – T-Closing Seam – 10 AUG 12
Close up inspection indicated material folds going into T-Seam closing weld area creating a leak path.
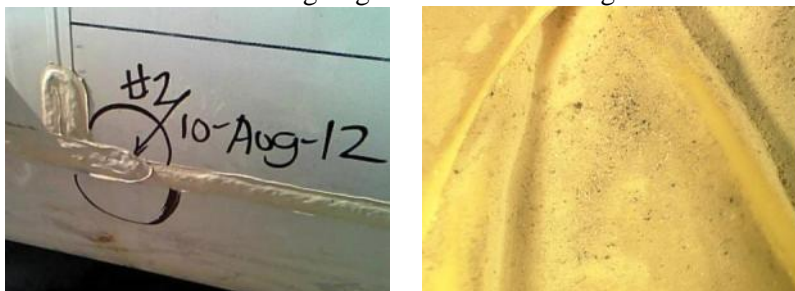
Figure 5.4.74 – Class II – T15-2 – Fitting – 10 AUG 12
Leak from around manway fitting within two months of fill. Manway plate needed to be removed and internal coupling bolts re-torqued.

Figure 5.4.75 – Class II – T16-2 – Corner – 20 JUN 12
A contaminant, suspected to be either adhesive or other compound, created a gap and a leak path by not allowing for weld seam contact.

Figure 5.4.76 – Class II – T17-8 – Closing Seam – 10 AUG 12
The compond appears to have been melted away due to overheating with the slinky bar. This created clear fiber disruption and exposure.

Figure 5.4.77 – Class II – T18-3 – Closing Seam – 27 JUL 12
RF weld tunneling including gaps in compound created at overlap of slinky bar

Figure 5.4.78 – Class II – T18-18 Closing Seam – 23 SEP 13
Slinky weld disrupted compound flow forming a crease and exposing scrim within crease. Discoloration of compound overheating.

Figure 5.4.79 – Class II – T20-1 – Corner – 20 JUN 12
Visual inspection revealed the same issue as T20-2
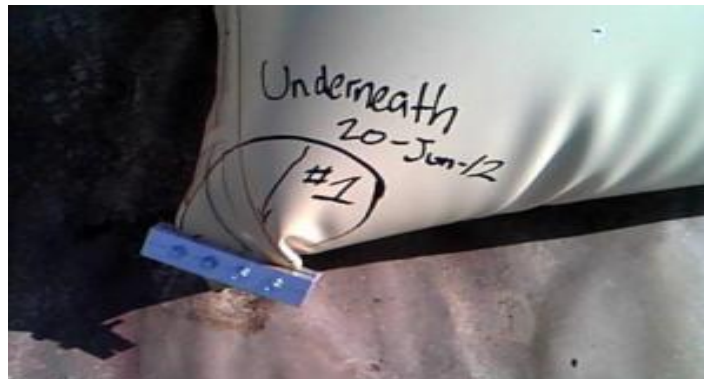
Figure 5.4.80 – Class II – T20-2 – Corner – 20 JUN 12
Over welding of compound exposing scrim in corner

Figure 5.4.81 – Class II – T24-4 – T-Seam Closing – 27 NOV 12
Adhesive applied to base material degradation

Figure 5.4.82 – Class II – T28-1 – Corner – 20 JUN 12
Air gun or extrudite gun miss causing scrim exposure, compound flow and gaps

The remaining figures are Class I leaks of interest

Figure 5.4.83 – Class I – T10-2 – Panel – 28 AUG 12
Compound contamination
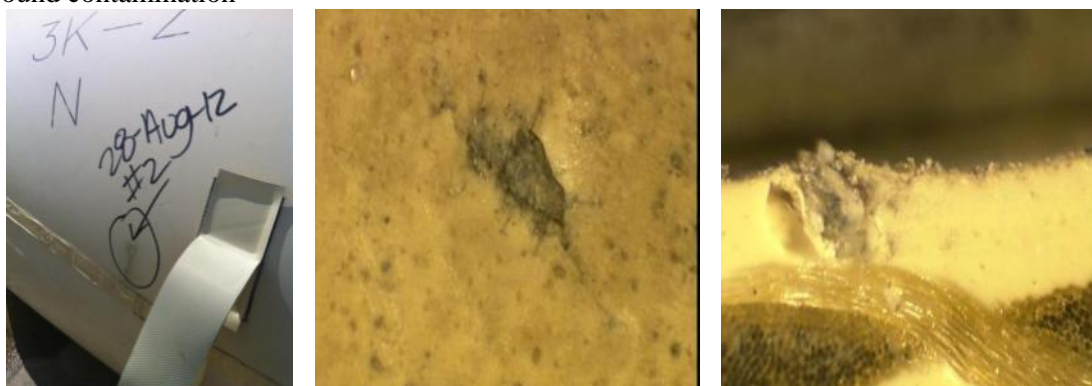
Figure 5.4.84 – Class I – T10-7 – Panel – 18 SEP 13
Hot air or extrudite gun miss forming crack in compound

Figure 5.4.85 – Class I – T15-10 – Panel CL1 – 5 JUL 13
External surface contamination or chemical cleaning agent
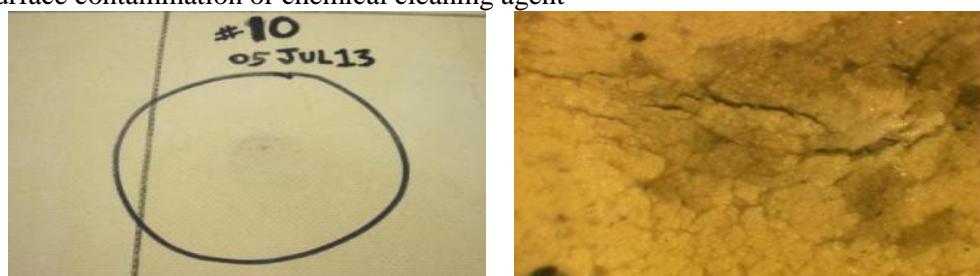
Figure 5.4.86 – Class I – T16-10 – Panel – 8 OCT 12
Compound contamination caused by hot air gun nick and associated pitting
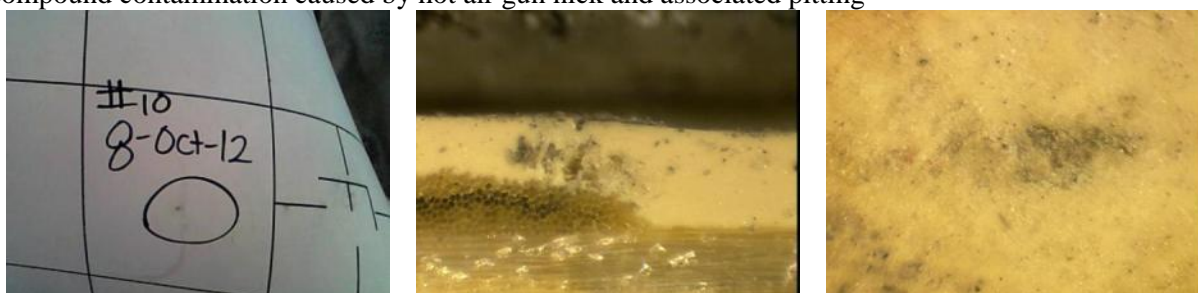
Figure 5.4.87 – Class I – T17-9 – Panel – 10 AUG 12
Potential external contamination based on cracking and discoloration near surface
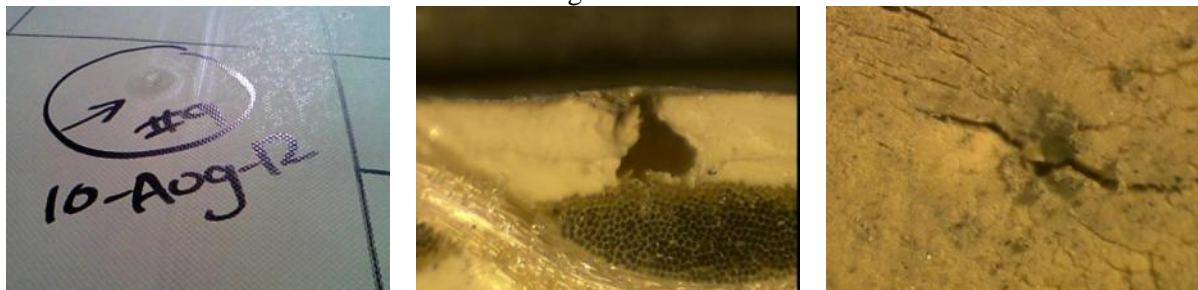
Figure 5.4.88 – Class I – T18-4 – Panel – 2 AUG 12
Hot air gun pitting or abrasion with subsequent contamination

Figure 5.4.89 – T19-34 – Class I – Panel – 26 NOV 13
External nick or disruption

Figure 5.4.90 – Class I – T20-12 – T-Seam Closing – 23 SEP 13
Localized compound stiffening and stress cracking caused by cleaning agent, adhesive or both

Figure 5.4.91 – Class I – T23-1 – T-Seam Closing CL1 – 23 SEP 13
Degradation of polymer due to cleaning agent or adhesive compound – closing procedure of seam

Figure 5.4.92 – Class I – T24-3 – Panel – 8 OCT 12
Internal coating contamination

Figure 5.4.93 – Class I – T24-12 – Panel – 6 NOV 13
External contamination source which also caused adjacent material wrinking

Figure 5.4.94 – Class I – T24-13 – Panel – 3 DEC 13
Internal contamination source due to up and out direction

Figure 5.4.95 – Class I – T25-4 – Panel – 6 NOV 12
Abrasion with fibers coming to surface only. No fiber bundle disruption hence did not manifest Class II seepage.

Figure 5.4.96 – Class I – T25-8 – Closing Seam – 10 JUL 13
Welding process coating disruption

Figure 5.4.97 – Class I – T26-5 – Panel – 29 MAR 13
Puncture or slit

Figure 5.4.98 – Class I – T26-6 – T-Seam Closing – 7 AUG 13
Overwelding of seam with excess compound flow and scrim exposure

Figure 5.4.99 – Class I – T26-11 – Panel – 3 DEC 13
Internal compound contamination

Figure 5.4.100 – Class I – T28-10 – Panel Seam – 18 JUL 13
Seam overwelding blisters
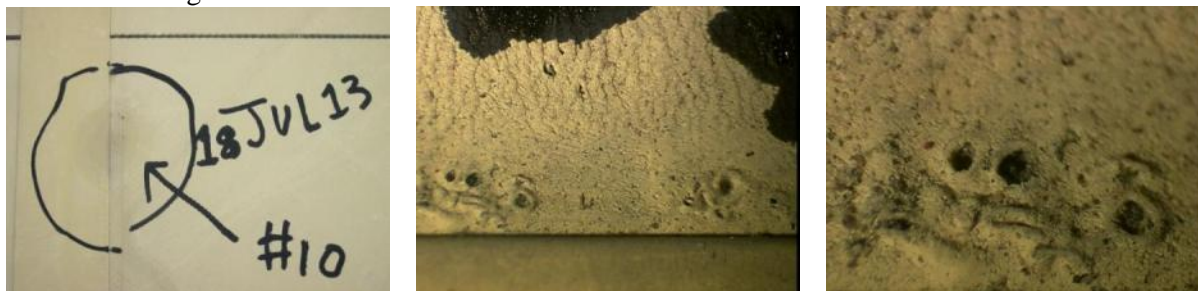
The following figures contain all the macro analysis results. What remains are all Class I leaks.

Figure 5.4.101 – Class I – T11-5 – Panel Seam Tape – 13 SEP 12
Warp weld leak – tape short, off-centered and not uniform on inside with wrinkles in adjoining fabric
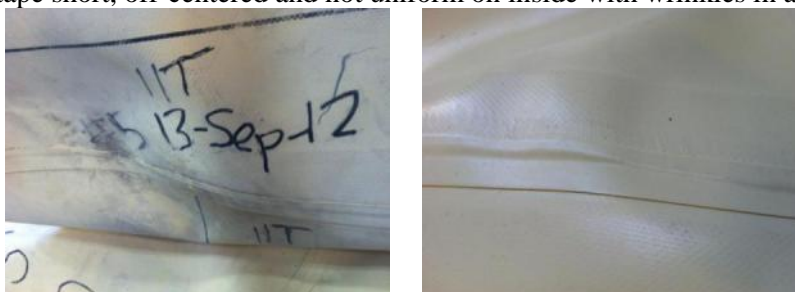
Figure 5.4.102 – Class I – T11-7 – Corner – 6 DEC 13
Exposed scrim on corner patch under clear extrudite compound on internal panel

Figure 5.4.103 – Class I – T12S-5 – T-Seam Closing – 22 OCT 13
Outer Acute T-Seam leak location with inner tape and material wrinkling
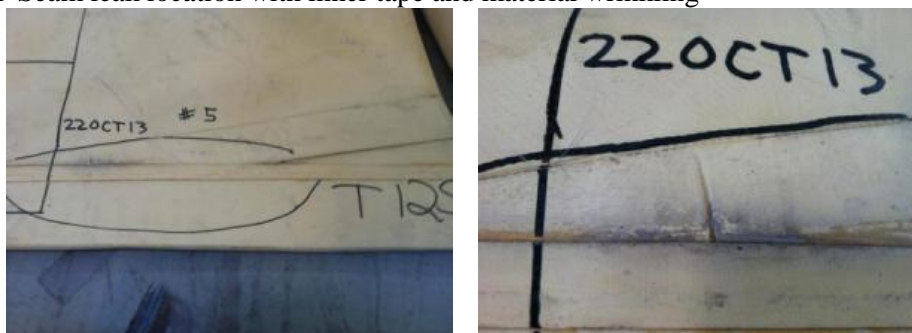
Figure 5.4.103 – Class I – T12S-5 – T-Seam Closing – 22 OCT 13 - continued
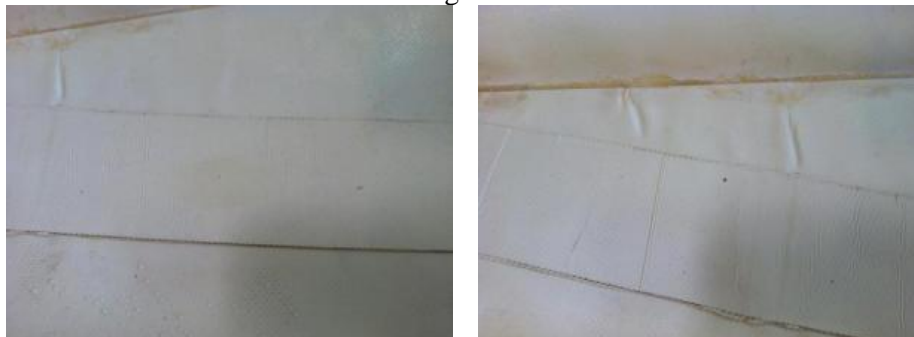
Figure 5.4.104 – Class I – T14-8 – Closing Seam leak – 12 JUL 13
Double butt seam gaps internal (right)
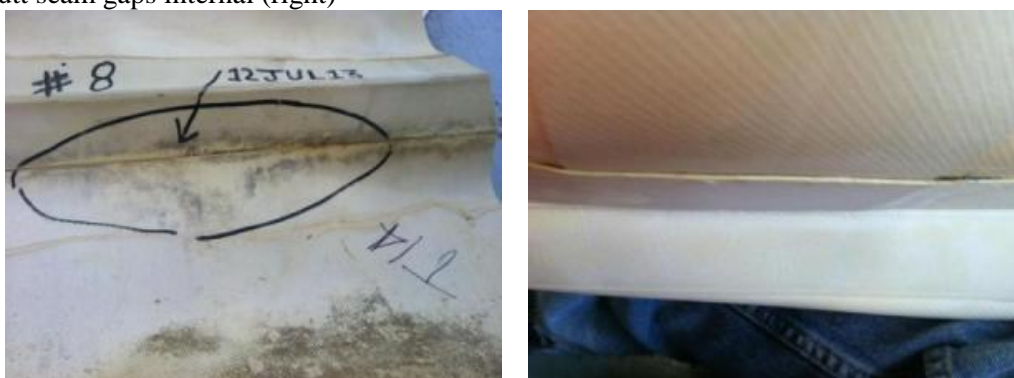
Figure 5.4.105 – Class I – T14-11 – Closing Seam – 18 SEP 13
Note wrinkles across weld throughout seam

Figure 5.4.106 – Class I – T15-11 – Closing Seam Tape – 25 SEP 13
Double butt seam tape gaps internal (right)

Figure 5.4.107 – Class I – T16#2-10 – Tape Gap – 26 AUG 13
Profile tape gap internal to #10 panel seam

Figure 5.4.108 – Class I – T17-24 – Vent Doubler – 27 SEP 13
Vent reinforcement ring cold weld (right)

Figure 5.4.109 – Class I – T17-19,16,17 – Closing Seam – 3 JUL, 19 AUG, 17SEP 13
Gaps between material panels encased in adhesive – example of single internal root cause for multiple external "family" of leaks

Figure 5.4.110 – Class I – T18-5 – Closing Seam – 28 AUG 12
Close up of leak #5 exterior showing ridge effect created by too much energy (right)

Associated inside closing seam #5 showing evidence of great ridge effect (left) compound flow, bubbling
and scrim exposure (right)
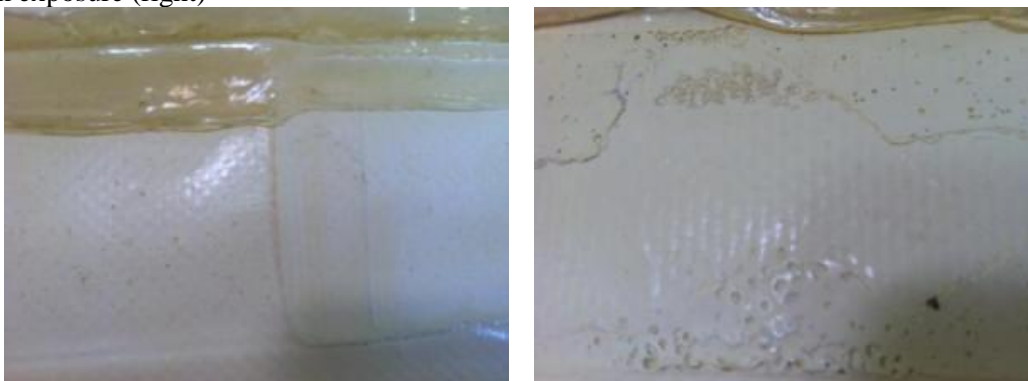
Figure 5.4.111 – Class I – T19-7 – Seam Tape – 10 AUG 12
Lack of tape adherance on inside of weld (right)

Figure 5.4.112 – Class I – T20-7 – Fitting Seam – 16 AUG 12
Close up showing tape cut line and overlap to right end of circled area (right)

Figure 5.4.113 – Class I – T20-6 – T-Seam Closing – 27 JUN 12

Close up of gaps at edges of FOPW / 2" RT interface (right). When FOPW was cut open, fuel was in the pocket.

Figure 5.4.114 – Class I – T22-9 – Panel Seam – 19 JUN 13
Pinched edge in seam with exposed scrim

Figure 5.4.115 – No Leak Observed – T24 – Found during extraction
Major wrinkle in bottom of Tank 24 closing cross seam – no leak noted, however, impossible to see in field

Figure 5.4.116 – Class I – T24-6 – T-Seam Closing – 27 NOV 12
Internal weld showing gaps and material puckering (left)

Figure 5.4.117 – Class I – T24-8 – Panel Seam – 10 JUL 13
1" reinforced tape overlap internal

Figure 5.4.118 – T25 – No Leak – Found during extraction
Internal tape overstretch tear / gap

5.4.7   Conclusions

The field test verification proved valuable for further understanding of CFTs and how to design and fabricate a better tank. Tanks were exposed to extremes relative to material stress, stretch and temperatures. The peak stretch attained was equivalent to or greater than those encountered in larger tanks exceeding the 7.7% fill and 1.7% warp threshold values. The prototype tanks (24-29) did not exceed the peak stretch values as often since they are designed to reduce stress for the same footprint and volume.

The design of the prototype tanks, the slight additional material (5-15%) and the fully supported tank footprint are all contributing factors in reducing the stretch and stress in the tank material.

Experimental stretch measurements confirmed both peak warp and fill stretch locations across the tanks. The "D" panel location, near the top center vent of the tank, exhibited the highest stretch in almost all cases. Contrary to published FEA models, the lowest typical stretch was measured consistently at "F", located in a tank corner. Lower stretch values were associated with tank features which involved multiple plies of material (e.g., manways and closing seams). Differences in warp panel seam types (e.g., SO, AO, DBS) seemed to have little or no impact on tank stretch (approximately 1% or less).

Over the test period, the fill and warp stretch both spiked (first 3-6 months) and then stabilized and reached an equilibrium point throughout the remaining 12 months of the test. Even though the tanks ran through a second summer, the continued temperature based stretch increase was not evident. Although temperature probably accelerated tank stretch during the initial summer months, it is believed that the initial tank fill (pressure) contributed more to the material stretch than temperature.

Average zero stretch values across the tanks were determined and plotted (Figure 5.4.31). Fill zero stretch was 3-5% and warp zero stretch ran typically from -0.5 to 1.0% across all tanks. The spread of stretch values differed across tank designs, with a typical standard or "pillow" tank design having a much broader maximum to minimum panel fill stretch range (5-7% typically) than a prototype tank (3% typically).

Temperatures varied throughout the study with summers averaging temperatures close to 85 °F and extremes in excess of 100 °F and winters with occasional drops below freezing and temperatures averages around 55 °F.

External skin temperatures correlated well with the ambient temperature. It was noted during testing that temperature did seem to have some impact on leak propagation, severity and rate.

The fuel shuttled between tanks remained relatively stable throughout the 18-month test period, with slight reductions in density, FSII, flash point and a slight increase in water content.

For each tank, a percent volume over target fill was established by verifying actual fill versus the original strapping chart. After a year of service it was found, on average, a 3,000 gallon tank would be exceeded by 10.79% or 324 gallons. It is thought this is due to the tank materials stretching during its first three to six months of over-filling. This was verified by graphical to-scale analysis of before and after pictures of the warp and fill tank images. The perimeter stretch analysis for a warp view (Tank 24) gave an increase of 1.2% while the fill view (Tank 27) value was 5%. This is consistent with the approximately 10% increase in volume.

There were 282 leaks logged across 21 tanks tested through a period of 18 months. Out of this total, 95.7% leaks were Class I, 3.9% leaks were Class II and 0.4% leaks were Class III (only 1 logged). There were <u>no cases</u> of seam separation, blistering or catastrophic failure.

Based on forensic inspection of leak samples extracted at the end of the study, leaks were further differentiated between field, manufactured and fabricated related sources. It was found that 54.6% were fabrication related and at most 1.8% was designated as potentially due to fabric manufacturing. The remaining leaks are either untraced fabrication issues, related to field based events during testing, storage, shipping or tank handling during testing and install.

The number of novel designs tested, 16 of the 20 tanks, definitely added to the number of leaks. In addition, the tanks being overfilled to 130 – 150% of designed capacity also impacted the leak propagation. New welding methods were employed by the fabricators and some of the prototype designs required unique material handling considerations. Fabricator design tanks had the best performance with an average of 9 leaks per tank. This was closely followed by the prototypes at 11 leaks per tank and the FY2008 tanks at 20 leaks per tank. The major contributing factors to the leaks, were the use of RF welding on multiple-ply seams (closing and corner) driven by tank designs, FY2008 corner clamp designs, prototype seam tape adherence (curved surfaces) and novel tank design and geometry considerations.

As ambient temperature increased during both summer seasons, the number of leaks appearing and the rate of fuel flow from each leak also increased. This leak appearance rate fluctuated between an average high of 22 per month during the summer to an average low of 3 per month during the winter (see Figure 5.4.68).

Closing seam and corner designs made up 58.4% of the aggregate leaks. This is due in part to the closing seam and corner designs employed in the 16 novel tank designs and illustrates the critical need of having fully-qualified, experienced fabricators enlisted in tank fabrication.

Fitting seam leaks could be dramatically reduced by verifying the tank fitting torque specification during deployment. In addition, leaks could be reduced by sealing or providing an O-Ring Compression style of design to block the path of fuel into exposed scrim.

BOTSS closing seams issues were mostly due to the radio frequency welding with a slinky bar. This seam was usually hit multiple times, especially in areas of weld overlap, which in turn caused too much compound flow and cross seam ridging or tunneling. For the DBS, a standard welding bar was utilized instead of a slinky bar. Occasionally there was compound flow and exposed scrim at the very end of a seam near a corner. The DBS RF seam, when it failed in dead load testing indicated cold welds.

Shingle overlap (SO), alternate overlap (AO) and double butt (BDS) panel seams all performed closely. The increased number in both AO and DBS can be attributed to multiple family leaks (single source) along the same seam logged late in the program. This was caused by the double butt seam (Tank 15 – DBS) and 2" reinforced tape (Tank 19 – AO) adherence issues.

Tank leak forensics of the 21 tanks tested provided valuable insight into and confirmed the root causes of many of the leaks.

6.0   Lab Testing

6.1   Dead Load Chamber (DLC)

6.1.1   FY2008 Test Summary

Historically, fuel tank seams have been evaluated through a combination of weld adhesion, seam shear and dead-load testing. The qualification for the material lot selected for this program met the requirements per MIL-PRF-32233, including face / back peel adhesion and RF / HAW weld adhesion. In addition, the FY2008 study (Contract No. SP0600-04-D-5442, Delivery Order 1017) established acceptable process weld adhesion thresholds based on the requirements of MIL-PRF-32233 and fuel immersions performed per ASTM D471. All 576 samples in the study were exposed to JP-8 jet fuel in the dead load chamber (DLC) under increasing temperature and load conditions. These temperature and load set-points were determined through a Time-Temperature-Stress-Superposition (TTSSP) model (Section 6.1.2) which allowed for accelerated testing. A correlation was verified between initial weld adhesion and samples tested in high temperature fuel (HTF). The data indicated that a 29 day dead-load value (equivalent to a 3 year service life) was obtained at a minimum HTF seam adhesion of 39 lbs$_f$/in. It was found that a 45 lbs$_f$/inch HTF seam adhesion (~15% above the minimum) translated into a 55 lbs$_f$/inch initial seam adhesion, which was considered the target for the seam specification (Figure 6.1.1). This became the basis for the process control plans developed for each welding method (Impulse, RF, Hot Air and Hot Bar) utilized in the experimental evaluation.

Figure 6.1.1 – Initial Weld and HTF Load Correlation
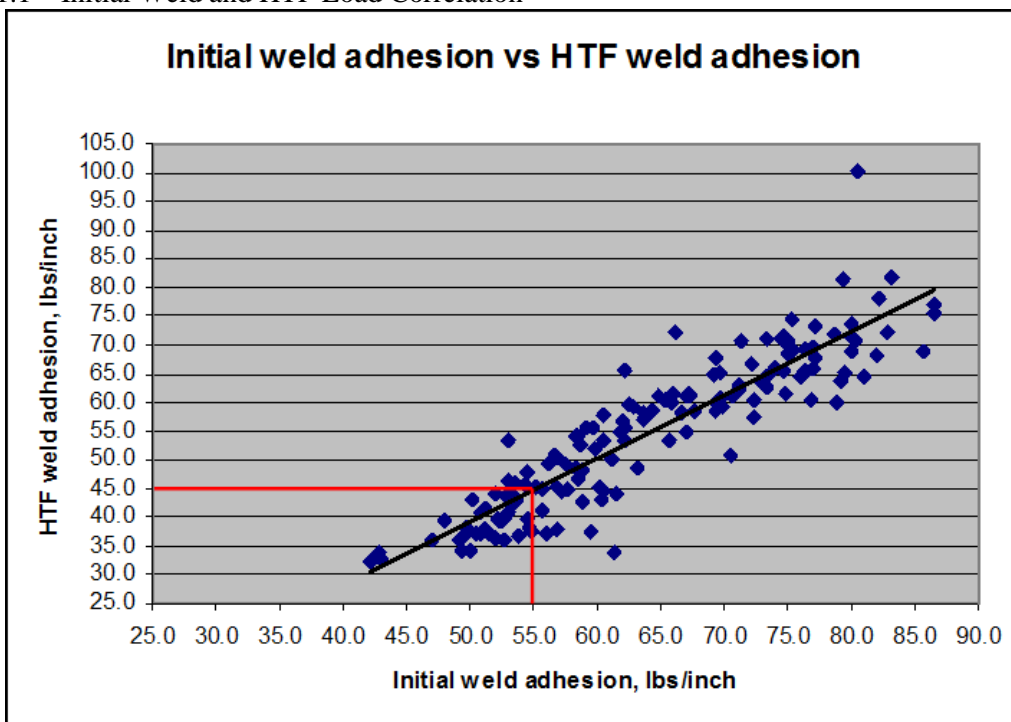
6.1.2   TTSSP Method

The Time-Temperature-Stress Superposition was established during the FY2008 program as an accepted method for accelerated dead-load testing of welded samples. This technique allows for the construction of long-term creep compliance curves based on a reference temperature (71° C, 158° F) and stress level (~ 119 lbs$_f$/in) adjusted by a temperature stress shift factor. These curves provided the basis for adjusting the exposure time for a temperature and a stress that is different from the reference temperature and stress.
The normalized data from the TTSSP model verified that samples that survived 29 days using the dead-load test protocol, would have met the 3 year service requirement (1190 days ~ 3.26 years). The model also assumed the load is 2.5 times the maximum in-plane stress that occurs in a full 50,000 gallon collapsible fuel tank at a service temperature of 158° F. The dead-load schedule for adjustment of the temperature and load applied is shown in Table 6.1.1.

Table 6.1.1 – Dead Load Time / Temperature / Load Schedule

DAY	TEMP	AIR LOAD
#	(°F)	(lbs)
0-9	160	120
9-20	160	135
20-27	160	150
27-34	160	175
34-41	160	200
41-48	180	200
48-55	180	225
55-62	180	250

The test was ended on Day 62 at a maximum temperature of 180 °F and a load of 250lbs$_f$/in.

6.1.3   Sample Selection Criteria

When the tanks for field testing were fabricated, a number of duplicate reserve tanks were also created from the same material lot. This was done in case any of the tanks in the field test would need to be replaced. All of the back-up tanks were fabricated under the same controlled process parameters as the original field tanks.

General, end closure and corner seam samples were identified for testing in the deadload chamber. These samples were cut to mirror the location of the welds in the field test tanks; including fabricator, FY2008 and prototype tank designs. Therefore, the results for both the lab and field tests should be representative of the tanks as a whole. The summary of the samples tested is listed in Table 6.1.2.

Table 6.1.2 – Dead Load Sample Summary

Tank Feature	Feature Description	Fabricator	Tank Types Represented	Seam Tapes Represented	Total Tanks	Additional Samples	Total Sample	Samples per	Total Samples
Panel Seam Type	Shingle Overlap (SO)	11, 18, 21, 27	Fabricator, Phase I, Prototype	1" PUT, 1"RT, 1" PRF	4	1	5	3	15
	Alternate Overlap (AO)	13, 28, 29	Fabricator, Prototype	1" PUT, 2" RT	4	0	4	3	12
	Double DBS (DBS)	15	Phase I	DBS	1	0	1	3	3
Closing Seam Type	Bottom Over Top Shear Seam (BOTSS)	11, 13, 18	Fabricator, Phase I	1" PUT, 1" RT	3	1	4	3	12
	Double Butt Seam (DBS)	15, 27, 29	Fabricator, Prototype	DBS	3	1	4	3	12
	Fold Over Prayer Weld (FOPW)	21	Phase I	1" PRF	1	0	1	3	3
	Warp vs. Fill Perpendicular (PER)	28	Prototype	2" RT	1	1	2	3	6
	Radius (RAD)	27	Prototype	1" PUT as cap strip, DBS	1	1	2	3	6
Corners	Tapered Triangle (TT)	11	Fabricator	1" PUT	1	0	1	3	3
	Trapezoidal Angle (TRP)	28	Prototype	2" RT	1	0	1	3	3
	Radius (RAD)	25	Prototype	1" PRF	1	1	2	3	6
									81

Several different seam types were tested in the dead load. Warp panel seams were tested to establish a baseline of field tank samples sealed with seam tape and other commonly-used scrim edge sealing compounds. This included shingle overlap (SO), alternate overlap (AO) and double butt seam (DBS) panel seams.

Closing seam types investigated included the bottom over top shear seam (BOTSS), double butt seam (DBS), fold over prayer weld (FOPW), the warp-fill perpendicular (PER) and the radius (RAD). The PER closing seam is found in the Transverse-T (Tank 29 – Figure 6.1.2) prototype, while the RAD closing seam is utilized in the Quonset hut (Tank 27) prototype. These seams were selected do the unique off-axis alignment of the panels. For the PER, the warp and fill directions of adjoining panels are welded together in a perpendicular orientation with a double butt seam. For the RAD closing seam, the warp direction of the "kidney shaped" end panel is welded to a fill panel at ~ 15° off axis orientation. These types of welds with a non-traditional orientation would result in potential fiber skew problems and would need to be evaluated.

Three unique corner orientations were also tested: the tapered triangle (TT), trapezoidal angle (TRP) and radius (RAD). The basis for including these tests again centered on the off-axis orientation of adjoining panels. The TT corner patch is representative of a fabricators tank design (Tanks 10-11). The TRP is unique to the corners of the trapezoidal prototype designs (Tanks 26 and 28 – Figure 6.1.3). The RAD design is common only to the prototype belly band design (Tank 25 – Figure 6.1.4).
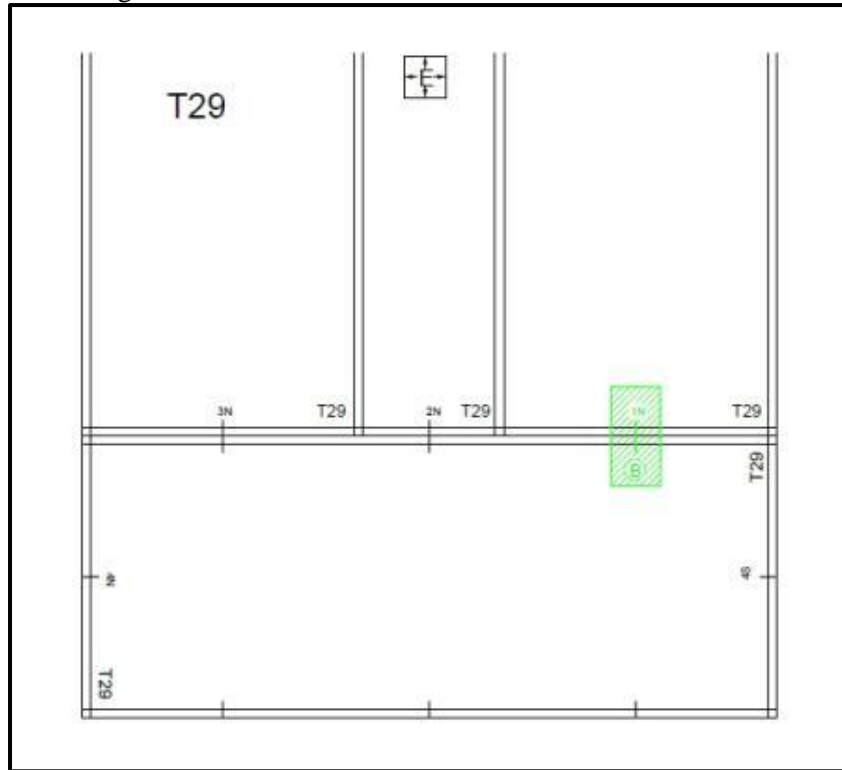
Figure 6.1.2 – PER Closing Seam on Tank 29 – "B"
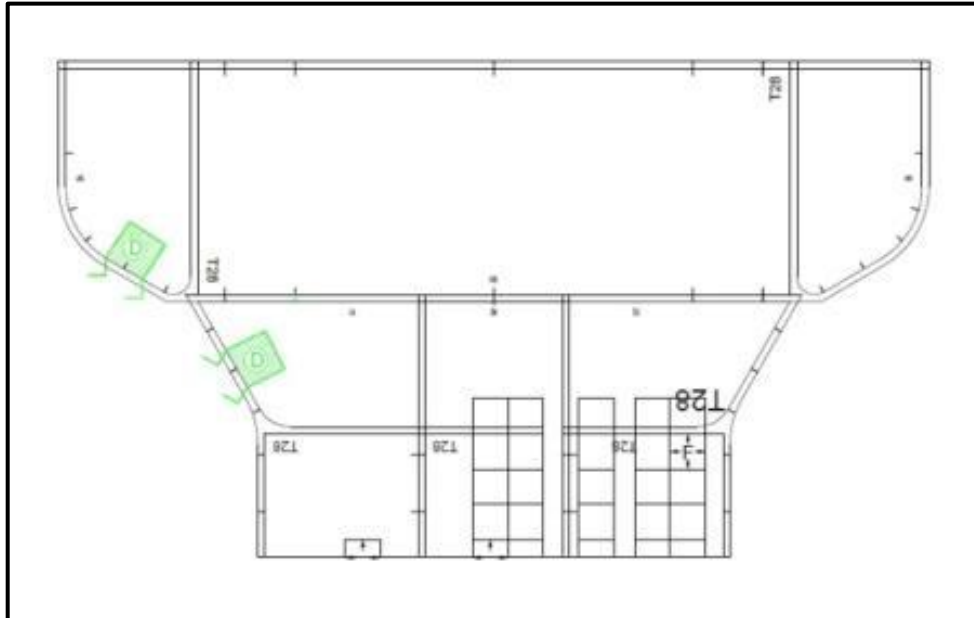
Figure 6.1.3 – TRP Corner on Tank 28 – "D"

Figure 6.1.4 – RAD corner on Tank 25 – "A"
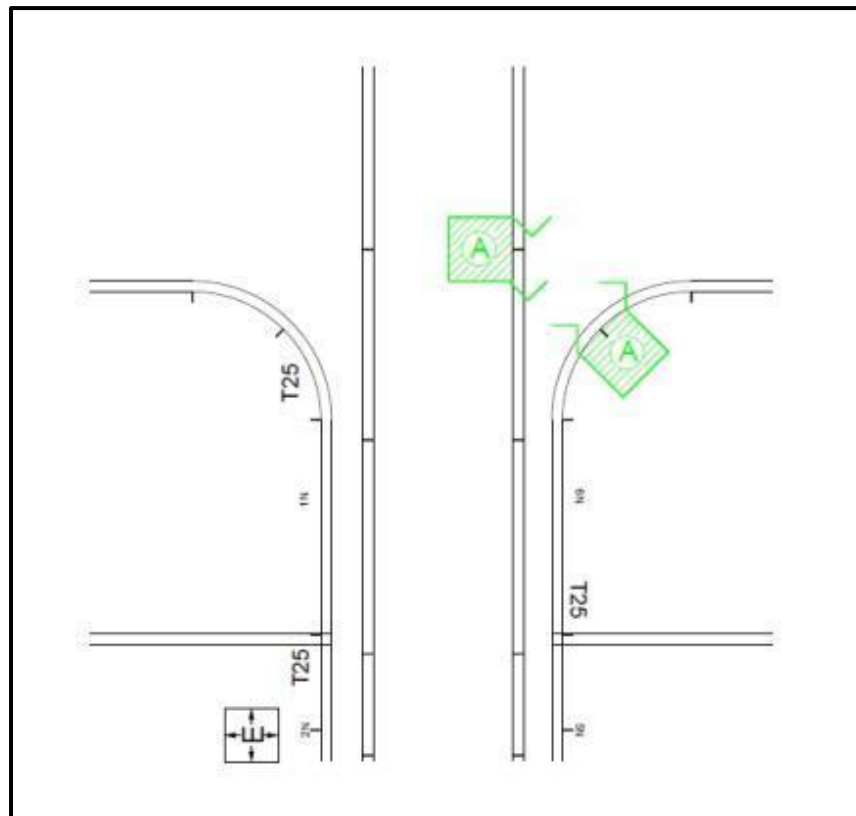
Figure 6.1.5 – RAD Closing Seam on Tank 28 – "C"
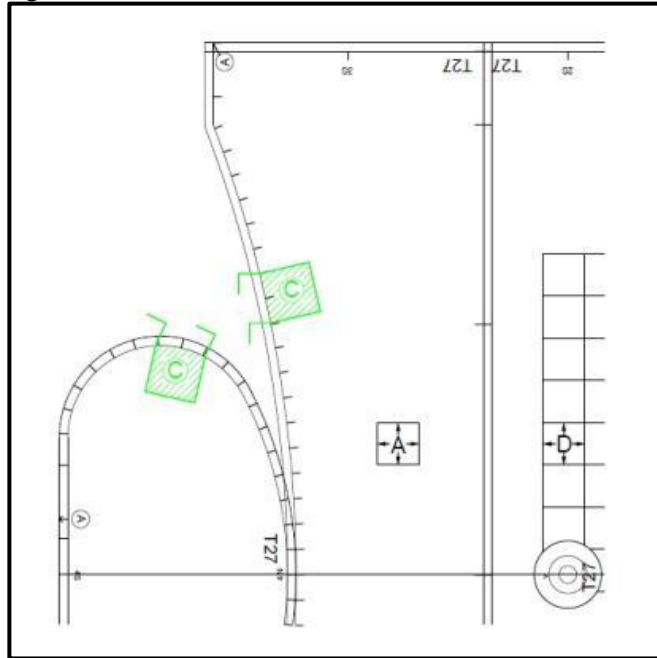
6.1.4   Seam Shear Verification Testing

A seam shear test per ATPD-2266 was performed on all the seams to verify their integrity prior to dead load testing. The seam shear result indicates whether damage may have occurred to the underlying greige good during the welding process. Excessive heating and/or pressure on the seam area potentially might damage the greige good contributing to premature breakage adjacent to the seam. The seam shear strength should coincide with the tensile strength of the material. An additional consideration is the adjacent panel orientation which poses a potential greige good skew issue.

Samples extracted from tanks were cut from wider swatches which allowed for additional material to meet the needs of all of the seam testing. Seam locations were selected for each tank based on the desired seam feature identified in Table 6.1.2. The specific location descriptions and associated seam shear results are summarized in Table 6.1.3. The majority of the seam shears' breaking strength and percent elongation values are above the acceptable value. The only two exceptions noted are both skew related, 25-2-B and 27-1-A. As can be seen referenced in the Direction column on Table 6.1.3, their orientations are F-45°R W/F and 15°F-W, respectively. For 25-2-B (Tank 25), this is a corner where the fill orientation of the "belly band" is welded roughly at the middle of the 24-inch radius corner of the top blanket (F-45°R W/F). For 27-1-A (Tank 27), this is where the warp orientation fibers of the side "kidney-shaped" panel meet the outside arc of the "hourglass" tank body at a point where the fill-thread orientation is off axis by approximately 15° (15°F-W).

Additional descriptive information in Table 6.1.3 includes the sample extraction location, the sample seam seal condition (i.e., use of tape, adhesive compound, both), the seam type designation, the orientation and the actual measured seam width. Warp-warp directional seams typically had higher values, but there were a few exceptions contingent on seam design.

Table 6.1.3 – Seam Shear Results and Associated Detailed Seam Descriptions

Tank #	Sample #	Seam Shear		Seam Seal		Location	Seam Type	Direction	Measured Seam Width (inches)	KEY
		Breaking Strength (lbsf)	Break Elongation %	Exterior	Interior					
11	11-2-A	447	43.4	1" PUT / TAN	1" PUT	Top "D" Panel Seam	W - SO	F - F (6°)	2.5	1" PUT - 1" polyurethane tape
	11-2-B	404	52.9	1" PUT / TAN	1" PUT / CLEAR	End "E" Panel Seam	W - SO	F - F (18°)	2.5	1" RT - 1" reinforced tape
	11-2-C	665	29.8	1" PUT / TAN	CLEAR	End Middle Closing Seam	CL - BOTSS	W - W	3	2" RT - 2" reinforced tape
	11-2-D	443	44.0	1" PUT / TAN	CLEAR	Trianangular Corner Seam	CNR - TT	W - TT	3	1" PRF - 1" profile tape
13	13-2-A	506	41.3	1" PUT	1" PUT	Top "D" Panel Seam	W - AO	F - F	2	CLEAR - clear sealant
	13-2-B	500	40.4	1" PUT	1" PUT	End "G" Panel Seam	W - AO	F - F	2	TAN - tan extrudite
	13-2-C	698	34.3	1" PUT	---	End Middle Closing Seam	CL - BOTSS	W - W	4	W - warp
	13-2-D	635	35.0	1" PUT	CLEAR	End End Closing Seam	CL - BOTSS	W - W	3.75	F - fill
15	15-2-A	571	54.6	DBS / CLEAR	DBS	Top "D" Panel Seam	W - DBS	F - F	4	SO - shingle overlap
	15-2-B	514	34.2	DBS	DBS	End "G" Panel Seam	CL - DBS	W - W	4	AO - alternate overlap
18	18-2-A	427	50.7	1" RT	1" RT	Top "B" Panel Seam	W - SO	F - F	2	DBS - double butt seam
	18-2-B	700	34.7	1" RT	CLEAR	End "E" Panel Seam	CL - BOTSS	W - W	2	CL - closing seam
21	21-2-A	533	44.8	1"PRF	1"PRF	Top "B" Panel Seam	W - SO	F - F	1.75	BOTSS - bottom over top shear seam
	21-2-B	489	36.8	1"PRF	---	End "E" Panel Seam	CL - FOPW	W - W	4.5	FOPW - fold over prayer weld
25	25-1-A	618	40.3	1"PRF	CLEAR	Bottom Corner Radius Closing Seam	CNR - RAD	45°R W/F - F	2	CNR - corner
	25-1-B	392	59.7	1"PRF / TAN	CLEAR	Top Corner Radius Closing Seam	CNR - RAD	F - 45°R W/F	1.75	TT - tapered triangle
27	27-2-A	512	46.1	1" RT	1" RT	Top "E" Panel Seam	W - SO	F - F	2	RAD - radius
	27-2-B	338	52.3	1" RT	1" RT	Side Radius "F" Closing Seam	CL - RAD	15°F - W	2	PER - perpendicular
	27-2-C	533	42.8	1" RT	1" RT	Side Radius "A" Closing Seam	CL - RAD	15°F - W	2	TRP - trapezoid angle
	27-2-D	696	41.5	DBS	DBS	Double Butt Strap Closing Seam	CL - DBS	W - W	4	
28	28-2-A	618	43.7	2" RT	CLEAR	Top "G" Panel Seam	W - AO	F - F	1.5	
	28-2-B	638	36.5	2" RT / TAN	CLEAR	Bottom Closing Seam	CL - PER	W - F	2	
	28-2-C	614	39.3	2" RT	CLEAR	Top Closing Seam	CL - PER	W - F	1.5	
	28-2-D	428	78.2	2" RT	CLEAR	Corner Closing Seam	CNR - TRP	F - W	1.5	
29	29-2-A	435	45.2	1" PUT	1" PUT	Top "E" Panel Seam	W - AO	F - F	2	
	29-2-B	634	52.6	DBS	DBS	Double Butt Strap Closing Seam	CL - DBS	W - F	4	
	29-2-C	496	47.1	DBS	DBS	"F" Closing Seam	CL - DBS	F - F	4	

6.1.5   Test Results

The number of days to seam failure was recorded for each of the deadload chamber test samples (Table 6.1.4). After failure, each test sample was removed and reviewed to determine the type of failure which occurred. The failure classifications utilized were originally defined in the FY2008 program.

In summary, those identified in this round of testing were:

- NF - Non Failure – The test sample lasted to the end of the dead load exposure period without a notable failure.

- IUS – Interply Urethane Separation – the separation occurred between the two inner urethane layers between the weld seams. In some cases, an inadequate "cold weld" possibly occurred (Figure 6.1.6 and 6.1.7).

- SW – Split Weld – a pull to base (PTB) occurs on both sides of the weld, with urethane weld "splitting" and being removed and adhering on both sides, in different areas (Figure 6.1.8).

- TIW – Tore Inside Weld – a tear occurred inside the weld area, typically parallel to the warp seam direction (Figure 6.1.9).

- TA – Tore Adjacent to Weld – the material on one piece tears parallel to the edge of the welded seam. A complete TA is shown below (Figure 6.1.10).

- TOW – Tore Outside Weld – the material on one piece tears, either partially or completely away from the weld area. It is directly related to testing and preparation (Figure 6.1.11).

- YSOS – Yarns Stripped-Out of Seam – some or all of the yarns are completely or partially pulled out of   the weld area (Figure 6.1.12).

The following failure criteria were not found in the review of the samples, but are listed for reference:

- PTB – Pull to Base – The urethane from one side of the weld was pulled away from the base fabric on the adjoining material.

- YBU – Yarns Bunched-Up – the urethane layer separates from one side of the weld, exposing the yarns. The load is then concentrated on the remaining attached area. The yarns will elongate causing bunching in the attached area and thinning of the yarns in the exposed area.

- ETL – End Tab Lift – the edge of the weld on one or both pieces, separates from the seam area from the edge, inward.

- SE – Scrim Exposure – The scrim is exposed on the coated fabric adjacent to the weld not in the yarn area associated with the edge of the seam itself. This can create a potential leak path.

Two additional categories were added due to the addition of both the off axis warp versus fill orientations and the edge sealing (SKEW and TAPE).

- SKEW – A twist of the samples or the pulling out of peripheral edge fibers due to the off axis fiber bundle orientation (Figure 6.1.13).

- TAPE – the tape used to seal the edge was not fully adhered and either the end was lifted or the tape was almost fully removed (Figures 6.1.14 and 6.1.15).

Figures 6.1.6 and 6.1.7 – Interply Urethane Separation (IUS) samples
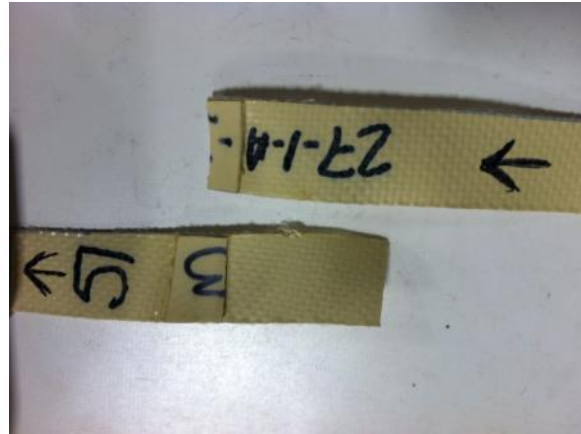

Figure 6.1.8 – Split Weld (SW) sample   Figure 6.1.9 – Torn Inside Weld (TIW) sample

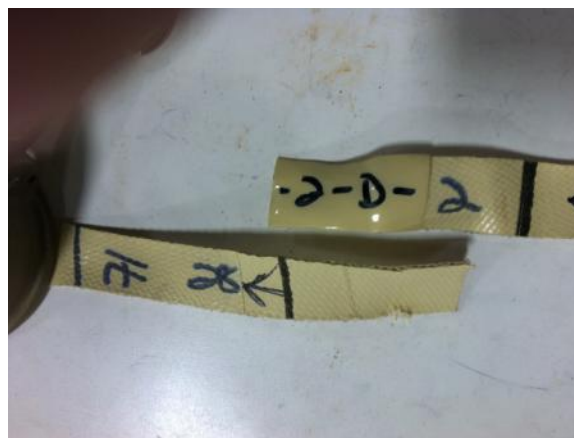Figure 6.1.10 – Torn Adjacent to weld (TA) sample

Figure 6.1.11 – Torn Outside of Weld (TOW) sample

Figure 6.1.12 – Yarns Stripped out of Seam (YSOS) sample

Figure 6.1.13 – SKEW example

Figures 6.1.14 and 6.1.15 – TAPE samples

The number of days to failure was logged for each sample. Upon visual inspection of the samples, a determination was made as to the way in which each sample weld failed. Descriptions developed in the FY2008 effort were then used to categorize and quantify all of the samples. A detailed summary of these results is presented in Tables 6.1.4.a and 6.1.4.b.

A number of relationships were graphed from the results to better understand the impact of tank design and fabrication factors on seam performance. Figure 6.1.16 illustrates the frequency of failure based on the failure mode descriptions previously presented. The percent frequency is based on the sample total of 81. Many of the seams had multiple failure modes associated with them, so the cumulative total of all designation percent frequency values exceeds 100%. For example, 25% (or 20 of the 81 total) samples did not fail.

Figure 6.1.16 – Dead Load Sample Failure by Frequency of Occurrence
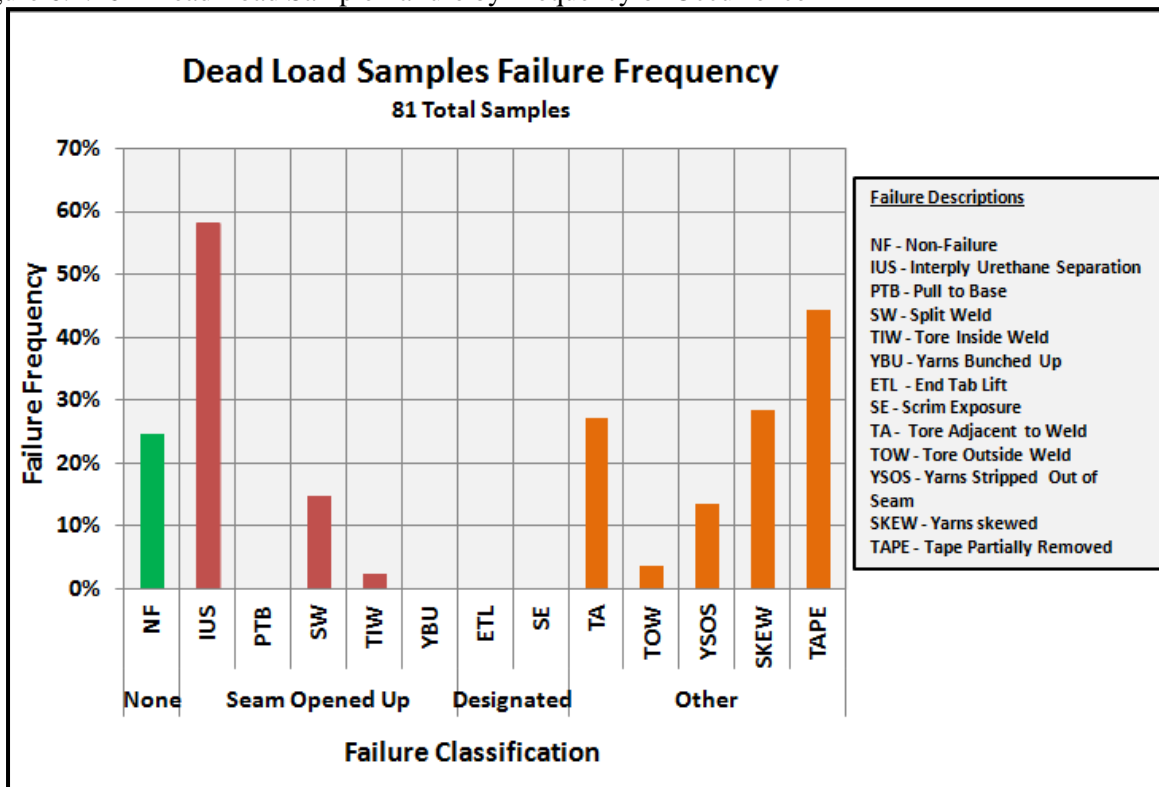
It was somewhat unexpected that the IUS or "cold weld" failure predominated at 58% or 47 samples. In addition, the range of samples for the IUS failure ran anywhere from 0 to 62 days. This ran counter to the field testing evidence, where no catastrophic seam ruptures or visual separations were recorded. Some of the split welds (SW) and tore inside weld (TIW) samples shared the IUS "cold weld" characteristic as well, with portions of the weld with little or no compound adherence. In these cases, it is assumed that the lack of total weld surface area adhesion precipitated the failure. All failures were at or within the weld seam area; the least desired failure type. By comparison, failures outside the weld area specifically tore adjacent (TA) and tore outside weld (TOW), only contributed to one-third of the total. Skew was noted in 28% of the samples. Tape adherence was predominant, occurring in 44% of the samples tested. Also contributing to this higher number were adherence issues associated with the prototype tapes, especially around curved or radius seams.

The non-failure assigned threshold was 63 days. On average, all failures except the TOW exceeded the 29 day, three-year equivalent service life. When rolling in the standard deviation for each failure mode, it was found that the SW, TIW, TA and YSOS failures all exceeded the 29-day, three-year threshold (Figure 6.1.17). By comparison, the IUS and TOW were much less likely to achieve the service life requirement. As expected, in most cases where a TOW failure occurred, sample SKEW was also present.

The corner design test results were somewhat expected due to the fiber orientation and skew associated with these designs. In addition the dead load test procedure typically is used to test samples with aligned fiber in the welds. The corner welds produced borderline results in the seam shear testing. This was a definite indicator of potential failure in the dead load testing. The difference between the RAD corner samples (A versus B) from Tank 25 was unexpected. The "B" top sample weld width was slightly under (1/8") the recommended weld width, while the bottom "A" weld width was to design. This may have had some impact on the difference seen in the dead load test results. The TRP samples tested were from tank corner welds which were nearly 25% narrower than the recommended design width of 2 inches. Paired with the off axis fiber orientation on this seam (30° off axis on adjoining panels), it possibly reduced its life in the dead load test.

Figure 6.1.17 – Days to Failure by Type
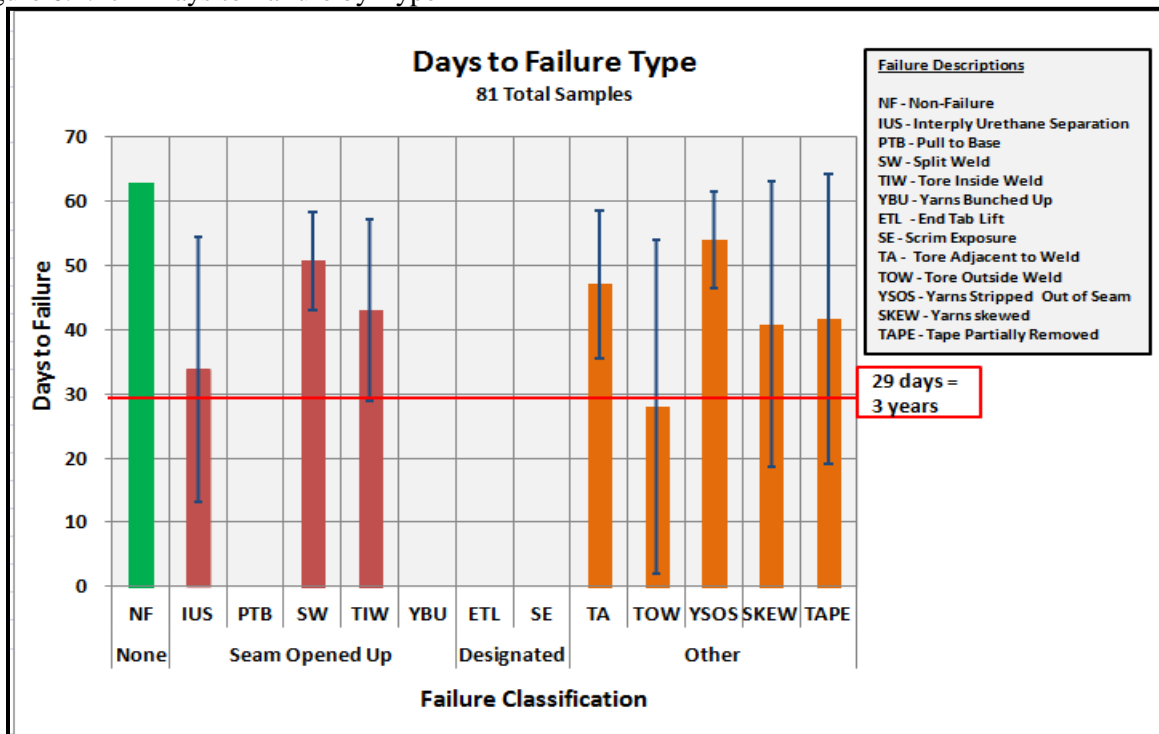
The final comparison looked at the average days to failure for each tank seam type. Although the SO and the AO seams are effectively the same, for the purposes of a dead load test, they resulted in strikingly different results for the warp panel seams. Based on the average and standard deviation, the SO, FOPW, RAD, TRP and SKEW were less predictable in this testing.

The DBS proved to be quite repeatable for both the warp and closing seams. The impact of SKEW on the variability of the dead load result is evident. This was expected since samples where fibers were not aligned across the seam typically lead to lower values. The TRP value was very low, but was based on a

limited sampling of 3. When reviewing values in 6.1.3, one would believe that the seam was integral based on the shear seam value. However, based on the weld width, at 1.5 inches, the skew and the associated IUS failure for all three, this seam had three different root causes that may have contributed to its premature failure. The PER seams, by comparison, were off of the same Tank 28, but exhibited much better performance.

The PER seams brought together adjoining panels that warp direction were offset by 90°. Across the six samples, however, they performed exceptionally. Unlike the TRP samples, SKEW was not noted in these samples.

The corner design test results were somewhat expected due to the fiber orientation and skew associated with these designs. In addition the dead load test procedure typically is used to test samples with aligned fiber welds. The corner welds produced borderline results in the seam shear testing. This was a definite indicator of potential failure in the dead load testing. The difference between the RAD corner samples (A versus B) from Tank 25 was somewhat surprising. The "B" top sample weld width was slightly under (1/8") the recommended weld width, while the bottom "A" weld width was to design. This had some impact on the difference seen in the dead load test results. The TRP samples tested were from tank corner welds which were nearly 25% narrower than the recommended design width of 2 inches. Paired with the off axis fiber orientation on this seam (30° off axis on adjoining panels), it undoubtedly reduced its life in the dead load test.

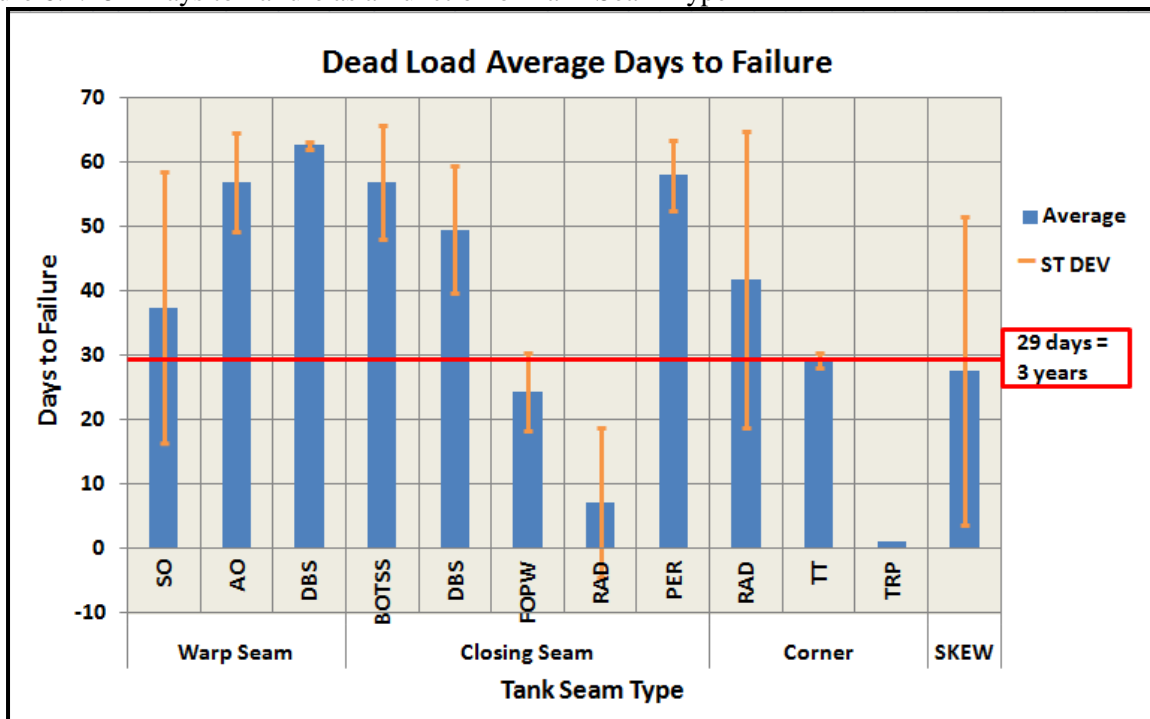Figure 6.1.18 – Days to Failure as a Function of Tank Seam Type

Table 6.1.4.a – Dead Load Test Sample Performance Log

TANK	SAMPLE LOCATION	CYLINDER	DAYS TO FAILURE	FAILURE COUNT	None	Seam Opened Up					Designated		Other					OBSERVATIONS
					NF	IUS	PTB	SW	TIW	YBU	ETL	SE	TA	TOW	YSOS	SKEW	TAPE	
11-2	A	1	53	1										1				
11-2	A	2	50	1		1							1					
11-2	A	3	49	1		1							1			1		
11-2	B	4	9	1		1												
11-2	B	5	11	1		1												
11-2	B	6	35	1		1										1		
11-2	C	7			1												1	
11-2	C	8			1												1	TAPE CRACKS FRONT AND BACK
11-2	C	9			1												1	
11-2	D	10	30	1		1							1			1		
11-2	D	11	28	1		1							1			1		
11-2	D	12	30	1		1							1			1		
13-2	A	13			1												1	TAPE LIFT BACK
13-2	A	14	53	1					1				1					
13-2	A	15			1												1	TAPE LIFT BACK
13-2	B	16			1													
13-2	B	17	49	1		1		1									1	TAPE LIFT BACK
13-2	B	18			1											1		SMALL SKEW
13-2	C	19	53	1		1											1	TAPE LIFT FRONT
13-2	C	20	33	1		1			1								1	TAPE LIFT FRONT
13-2	C	21	53	1									1		1			
13-2	D	22	49	1		1												
13-2	D	23			1												1	BW BACK SIDE SEPARATION
13-2	D	24			1												1	BW BACK SIDE SEPARATION
15-2	A	25			1													NECKING OUTSIDE WELD
15-2	A	26			1													NECKING OUTSIDE WELD
15-2	A	27	62	1		1		1										
15-2	B	28	49	1		1		1										
15-2	B	29	49	1		1		1										
15-2	B	30	53	1		1		1										
18-2	A	31	53	1		1		1							1			TAPE LIFT BACK
18-2	A	32			1										1		1	TAPE LIFT BACK / FRONT, SKEW/ PARTIAL IUS
18-2	A	33	60	1		1		1										TAPE LIFT BACK
18-2	B	34	60	1									1		1			
18-2	B	35	60	1									1		1			SEALANT CRACK F/B
18-2	B	36	60	1									1		1			
21-2	A	37	40	1		1							1					TAPE LIFT BACK / FRONT
21-2	A	38			1												1	TAPE LIFT PROFILE
21-2	A	39	34	1				1					1		1		1	TAPE LIFT PROFILE
21-2	B	40	18	1		1											1	TAPE LIFT FRONT
21-2	B	41	30	1		1												
21-2	B	42	25	1		1												

Table 6.1.4.b – Dead Load Test Sample Performance Log

| TANK	SAMPLE LOCATION	CYLINDER	DAYS TO FAILURE	FAILURE COUNT	None NF	Seam Opened Up IUS	PTB	SW	TIW	YBU	Designated ETL	SE	Other TA	TOW	YSOS	SKEW	TAPE	OBSERVATIONS
25-1	A	43			1											1		
25-1	A	44			1											1		SLIGHT
25-1	A	45	35	1									1					
25-1	B	46	40	1									1			1	1	TAPE LIFT FRONT
25-1	B	47	1	1										1		1		CUT IN SAMPLE?
25-1	B	48	49	1		1							1			1	1	TAPE LIFT FRONT
27-2	A	49	30	1		1							1				1	TAPE TORN/BS TAPE LIFT
27-2	A	50	11	1		1											1	TAPE TORN/BS TAPE LIFT
27-2	A	51	1	1		1											1	TAPE TORN/BS TAPE LIFT
27-2	B	52	0	1		1											1	TAPE TORN/BS TAPE LIFT
27-2	B	53	1	1		1											1	TAPE TORN/BS TAPE LIFT
27-2	B	54	30	1		1											1	TAPE TORN/BS TAPE LIFT
27-2	C	55	2	1		1											1	TAPE TORN/BS TAPE LIFT
27-2	C	56	9	1		1											1	TAPE TORN/BS TAPE LIFT
27-2	C	57	1	1		1											1	TAPE TORN/BS TAPE LIFT
27-2	D	58	30	1		1											1	DBS EACH SIDE
27-2	D	59	49	1		1											1	DBS EACH SIDE
27-2	D	60	54	1		1											1	DBS EACH SIDE
28-2	A	61			1											1		SLIGHT
28-2	A	62			1													CRACK SEALANT BACK
28-2	A	63	54	1		1		1					1		1			
28-2	B	64			1												1	SOME PTB, TAPE LIFT, PARTIAL YSOS,
28-2	B	65	53	1		1							1		1		1	CRACKED SEALANT BACK, TAPE LIFT,
28-2	B	66			1												1	TAPE / EXTRUDITE LIFT
28-2	C	67	53	1				1										
28-2	C	68	53	1		1		1									1	TAPE TORN
28-2	C	69			1													
28-2	D	70	1	1		1										1		1" WELD WIDTH, TAPE TORN
28-2	D	71	1	1		1										1		1" WELD WIDTH, TAPE TORN
28-2	D	72	1	1		1										1		1" WELD WIDTH, TAPE TORN
29-2	A	73	49	1		1										1	1	TAPE TORN
29-2	A	74	60	1		1								1		1	1	TAPE TORN
29-2	A	75	40	1		1		1									1	TAPE LIFT
29-2	B	76	61	1									1		1	1		
29-2	B	77	53	1									1		1	1		
29-2	B	78	53	1									1		1	1		
29-2	C	79	54	1		1										1		
29-2	C	80	60	1		1											1	TAPE TORN
29-2	C	81	30	1		1								1		1		
		TOTAL FAILURES ›	61	20	47	0	12	2	0	0	0	22	3	11	23	36		
		SAMPLE %	81	25%	58%	0%	15%	2%	0%	0%	0%	27%	4%	14%	28%	44%		

6.1.6   Conclusions

In summary, 81 samples were identified and extracted from a cross section of 9 representative duplicate tanks for dead load testing. The samples were selected based on being representative of all the seam types, locations, panel orientations and seam tapes utilized in the field study. For the testing, the dead load chamber (DLC) developed for the FY2008 effort was reused. The test method employed was the proven TTSSP model, which allowed for accelerated testing under stepwise increases in temperature and load. The normalized data from the TTSSP model verified that samples that survived 29 days using the dead-load test protocol would have met the three-year service requirement (1190 days ~ 3.26 years). The model also assumed the load is 2.5x the maximum in-plane stress that occurs in a full 50,000-gallon collapsible fuel tank at a service temperature of 158° F.

Seam shear tests per ATPD-2266 were conducted on all the seams to verify their integrity prior to dead load testing. This was done to indicate whether damage may have occurred to the underlying greige good during the welding process or bias introduced through a design based adjacent panel greige good skew orientation. Only two skew related exceptions, 25-2-B and 27-1-A, did not meet the minimal acceptable breaking strength of 400lbs$_f$/in because of the fiber orientation at the point of the seam and the test procedure.

Figure 6.1.19 summarizes the frequency of failure as a function of the tank design feature. For each tank feature multiple failure conditions were noted. As stated previously, more than one failure type may exist per sample. For example, a dead load sample which undergoes an IUS may also exhibit TA and SKEW, like cylinder 12 in Table 6.1.4.a. A seen in Figure 6.1.13 the impact of SKEW is clearly evident to a greater degree in those seams with off axis fiber orientation (RAD, TT and TRP). The Seam Opened Up categories, in particular the IUS, was predominant and indicated that seam failures were frequently due to inadequate welding. By comparison, the OTHER weld failures (TA, TOW, and YSOS), usually associated with over-cooking the weld area or with test fixture issues, was generally less frequent.

The evaluation of the dead load data focused on the frequency of the welded seam failure type and the number of days to failure based on seam type. A total of 20% of the total samples (16 out of 81) did not meet the 29-day, three-year service requirement. Of the 16 premature failures, 15 were associated with IUS or "cold welds" and the remaining one with a TOW / SKEW failure that could be attributed to the weld orientation (Tank 25 – belly band / corner radius weld). The total number of IUS failure welds (58% – 47/81) was surprisingly high and points to the need for evaluating closing off-axis orientation welds when fabricating tanks.

Figure 6.1.19 – Failure Frequency by Design Feature
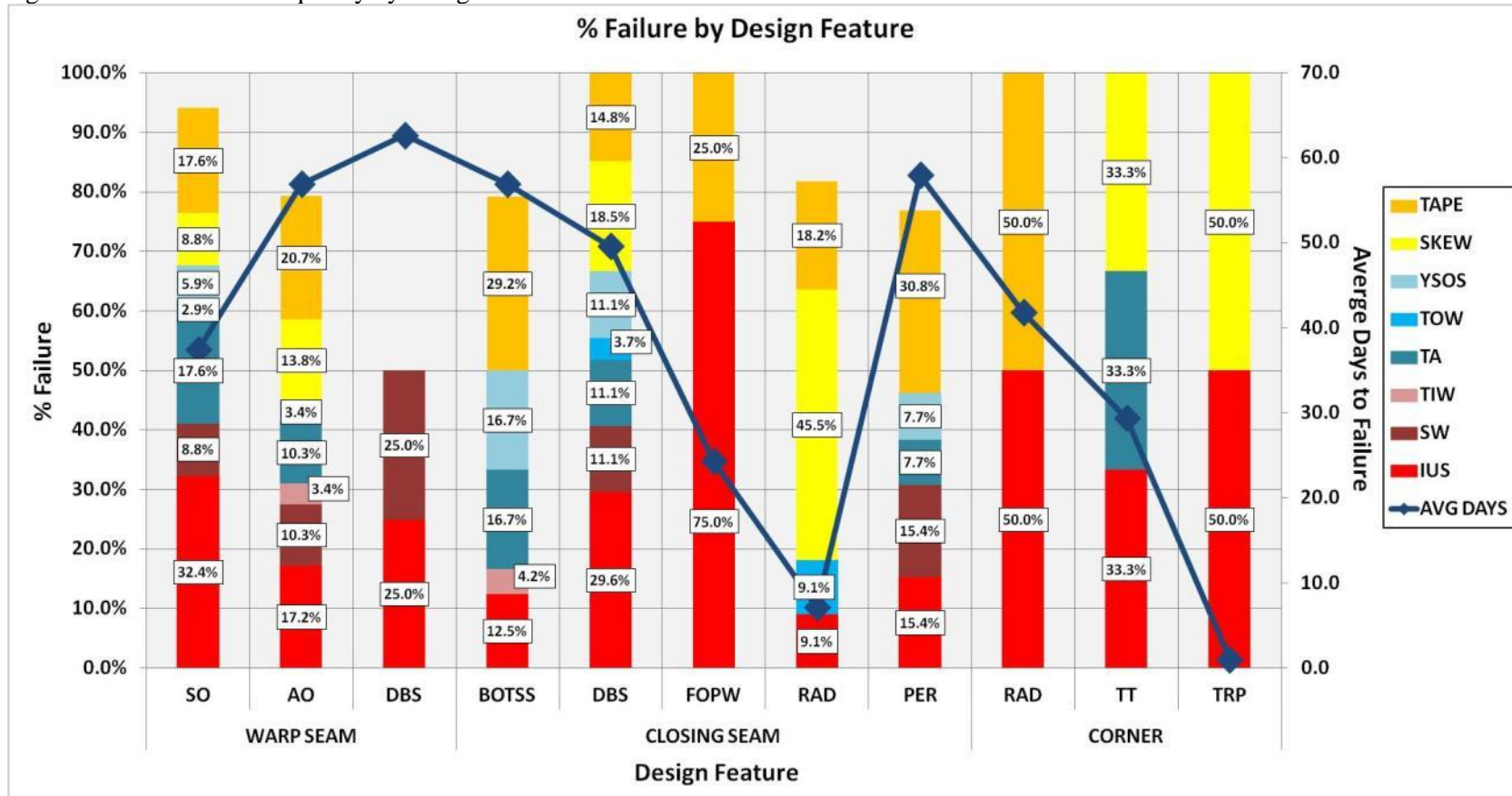
6.2   Leak Test Rig (LTR)

6.2.1   LTR Design and Operation

The Leak Test Rig (LTR) is a unique test chamber specifically designed to help model and better understand the factors that contribute to the formation of leaks in collapsible fuel tanks. A 30-gallon square, welded steel chamber was built to hold tank material samples of at least 36 inches square. Once secured over the opening of the chamber, a specially designed top clamping frame held and sealed the material in place. The chamber was constructed with sufficiently thick steel to allow for fluid pressures in excess of ½ psig at temperatures up to 140 °F. The schematic in Figure 6.2.1 details an orthogonal, top and side views of the assembled chamber. Figure 6.2.2 shows two different views of the assembled chamber. Figure 6.2.3 is a schematic of the LTR system plumbing and instrumentation. Comprehensive detail of the chamber design and operation can be found in Appendix V.

Figure 6.2.1 – Leak Test Chamber Design

Orthogonal - Limited Detail (NTS)

Complete Assembly
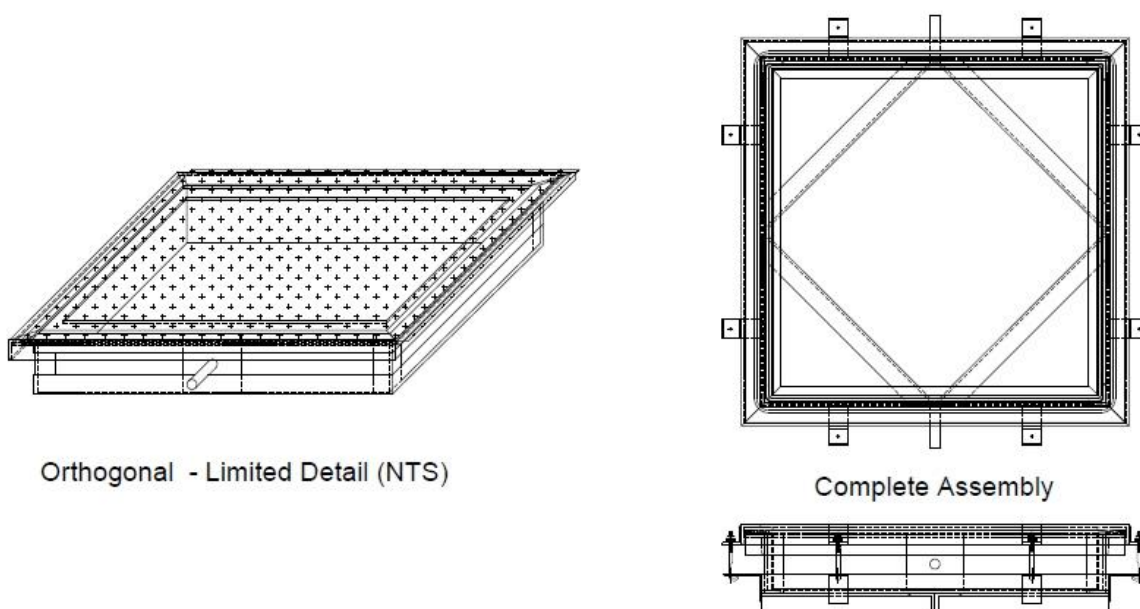
Since air removal and draining of the chamber were determined to be critical, the chamber was designed to pivot around two centrally-located pins on each side between vertical beams of a structural support stand (Figure 6.2.2). In addition, the stand was elevated on the left side with a 3" structural support base to facilitate air removal through the vents in the upper left side of the chamber.

Figure 6.2.2 – Leak Test Chamber Pivot in Vertical Frame

Figure 6.2.3 – LTR System Schematic
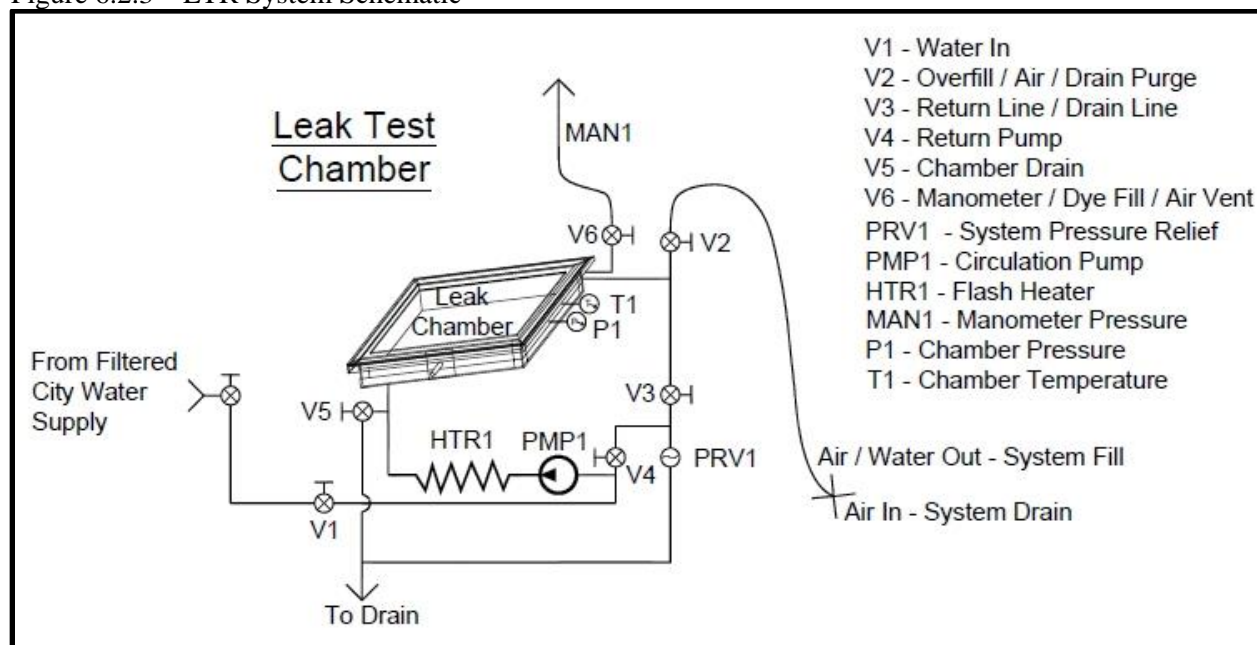
6.2.2   Sample Selection Criteria

The LTR was designed to study mechanisms which create and or contribute to leaks in polyurethane tanks in a controlled test environment. The unique LTR design achieved this by maintaining continuous exposure of the test samples at target temperature and pressure.

The samples tested consisted of two types: samples extracted from fabricated tanks and those fabricated to replicate seams or flaws typically seen in tanks. A total of 18 tests were conducted. The samples that were fabricated specifically for this test included panel / closing seam types as well as panel flaws typically seen in tank use. For the seams, shingle overlap (SO), alternate overlap (AO), single (SBS) and double butt seams (DBS) were tested. Panel damage studied included material scuffs on both the inside and outside of the tank body, damage due to incidental hot air gun or cleaning with off label chemicals, pin holes and material folding and compression. Tank features tested included seams, problematic closing areas (T-Seams) and fittings. Corners were originally considered as an additional potential test to investigate, however, sealing the corner samples into the test rig proved to be problematic. In addition, tank field performance provided abundant evidence as to the root cause of corner leaks (Section 5.4.6).

Shingle, alternate and double butt seams evaluated are as described previously in Section 4.2, Figures.4.2.4 to 4.2.6. For all seam samples fabricated specifically for this test, tape was not used to cover exposed scrim. The single butt seam (SBS) sample was created to fully understand the impact between a single and double butt seam (DBS) in terms of fluid penetration.

Manway fittings designs were selected specifically to look at the standard configurations supplied by the tanks fabricators, as well as the O-ring compression design.

Upon completion of the scheduled testing, it was decided to add two additional pin-hole studies to further focus on differentiating the impact of pressure and temperature. This was done with pinholes made with 0.013-inch and 0.075-inch diameter pins.

6.2.3   Test Results

Table 6.2.1 details both the test conditions and the results. Table 6.2.2 summarizes the conditions and results of the additional pin-hole test. A description of the critical findings of each test follows.

Table 6.2.1 – Leak Test Rig Test Conditions and Results

Tank Feature	Feature Description	Test Panel Description	LTR Fabricated Sample	Tank Sample	Duration (hrs)			Temperatures (°F)				Chamber Gauge	Manometer Pressure	Leak	Result Description
					Total	Heating	Cooling	Max Heat Avg	Max Heat	Min Temp	Overnight Start	(in H₂O)	(in H₂O)	(Y/N)	
Panel Seam Type	Shingle Overlap	Centered Shingle Overlap w/o tape	Y	N	20	4	16	138.4	138.4	70	80.4	4 -17	4 -17	Y	Immediate leaks at T-seams and scrim sides. Overnight leaks on all seams.
	Alternate Overlap	Centered Alternate Overlap w/o tape	Y	N	26	11	15	140.4	142.6	69	87.4	5.5 -18	5 -18	N/Y	Minimal leaks, T-seams (corners), some scrim
	Butt Seam	Centered Single Butt Seam Inner / Outer	Y	N	25	10	15	140.2	143.3	70	88	5 -19	5 -19	Y	Dye penetration into panels at open underside of butt weld
	Butt Seam	Centered Double Butt Seam	Y	N	25	7	18	139.7	142.2	70.4	70.4	4 -18	4 -18	N/Y	No dye penetration into panels adjoined by butt straps - penetration through overlap welds
Other	Panel	Inside / outside scuff	Y	N	50	22	28	140.4	145	61.8	89.8	5 - 13	5.5 - 14	N	No leaks present - test suspended. Rerun with deeper scuff + fiber breakage
		Inside / outside scuff	Y	N	44	9	35	140.6	143	69	87.4	5 - 18	5 - 18	Y	Leaks present at all scuffs. See report details. Leak appearred after 2nd morning refill.
		Hot air gun tip	Y	N	1	0	1	72.3**	n/a	71.4	n/a	4 - 15	3.5 - 15	Y	Immediate major leak - test discontinued to protect pump
		50 lb Fold / Compress	Y	N	Sample not tested due to lack of impact on material										
		MEK / THF + Fold / Compress	Y	N	21	4	17	140	141	68.6	68.6	5 - 13.5	5 - 13.5	Y	Leak appearred after 2nd morning refill.
		Pinhole	Y	N	43	10	33	140.5	144	68	87.4	4.5 - 15	5 - 14.5	N	No leaks - pinholes offset inside and out on same fiber rows
		0.013 DIA Pinhole	Y	N										Y	Special test - see additional table 6.2.2
		0.075 DIA Pinhole	Y	N										Y	Special test - see additional table 6.2.2
Fittings	Manway	Standard Manway	N	Y	43	10	33	141.5	144	67.8	86.2	3 - 16.5	3 - 16	Y	Bolts 11-20 < 5 ft-lbs (left), bolts 1-10 = 5 lbs (right) - no leaks until bolts loosened
			N	Y	42	13	29	140.4	141	65.6	88.2	5 - 18	5 - 18	N	All bolts ≥ 10 ft-lbs
		O-Ring Compression	N	Y	30	14	16	140.2	143.2	70	86.6	6 - 16	6 - 16	Y	All bolts ≥ 10 ft-lbs - no leaks until bolts loosened
Seam Tape	1" Reinforced	Shingle Overlap / Loosened tape edge	N	Y	23	7	16	139.9	140.4	73.2	78.2	4 - 18	4 - 18	Y	Clear to milky white effluent from tape lift Accidental through hole penetration in panel
	2" Reinforced	Alternate Overlap / Loosened tape edge	N	Y	23	7	16	139.6	141	86.2	89	4 - 18	4 - 18	Y	Clear to milky white effluent from tape lift Accidental through hole penetration in panel
	Profile	Shingle Overlap / Loosened tape edge	N	Y	23	7	19	141.5	143.2	82	87	4 - 18	4 - 18	Y	Clear to milky white effluent from tape lift Accidental through hole penetration in panel

6.2.3.1 – Seams

The fabricated seam samples tested included the shingle and alternate overlap, single and double butt seam designs. In addition, multiple T-Seam configurations were tested as seam samples welded into frames for LTR mounting. Seam tape was not added to the exposed scrim of the fabricated panels; seam tape samples were already represented through the extracted tank samples.

Critical to this testing is the discussion of pressure within the tank. As a tank is filled to capacity, the fuel reaches equilibrium with the counter acting force of the material. The net effect is a resident pressure in the tank of ≤ ½ psi above ambient pressure. Due to the height of the vent stack, the visible fluid column associated with this slight pressure differential is typically unnoticed. When a tank is overfilled, the fluid overflows the vent and spills out over the tank body.

6.2.3.1.1. – Centered Shingle Overlap (SO)

The shingle overlap seam is representative of many of the warp panel welds in tank designs currently in service. As the name suggests, each panel is added to the base blanket in a "shingle" overlap much like the overlapping pattern on a roof shingle. This is commonly used due to ease of fabrication and or fabricator equipment or process constraints. The down side to this weld is that it introduces a potential inside to outside fluid path, as previously illustrated in Section 4.2, Figure 4.2.4. This was clearly illustrated in the SO test results.

Figure 6.2.11 – Overall view of external SO seam locations ①, ② and ③.
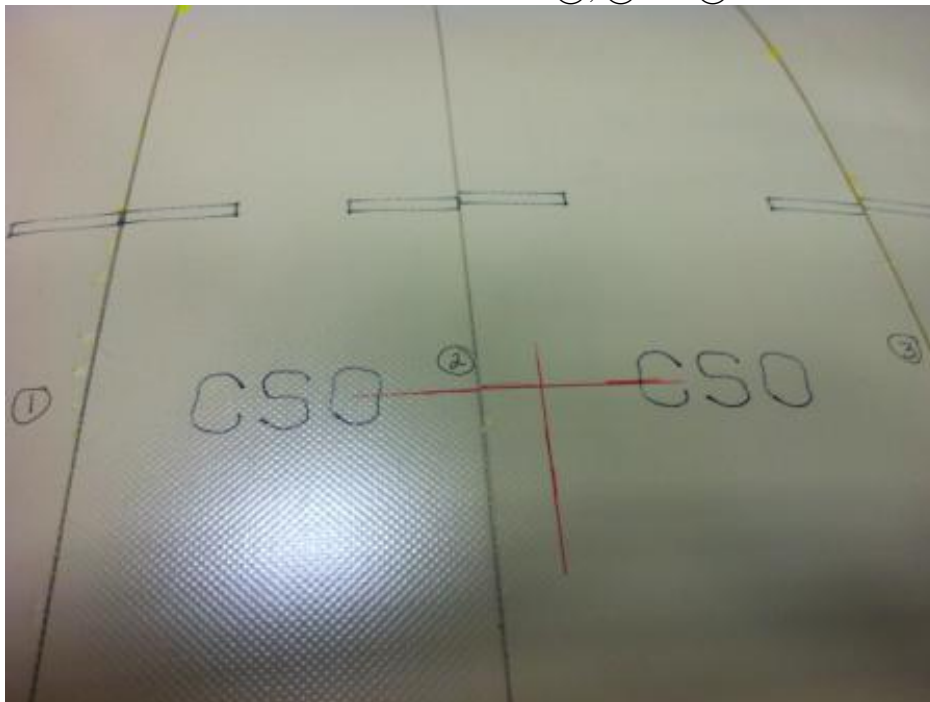
Immediately after the test was initiated and the system pressurized to ≥15 inches H_2O, leaks began to appear. This was before the system even had an opportunity to heat up. The first leaks appeared at the T-Seams at the exterior open scrim edges ①, ② and ③. The leaks were more predominant near the top and bottom of the seams, becoming more uniform across the seam as the test continued. Note the individual droplets appeared along seam.

Figure 6.2.12 – Perpendicular and parallel views of SO outer seam showing individual droplet formation
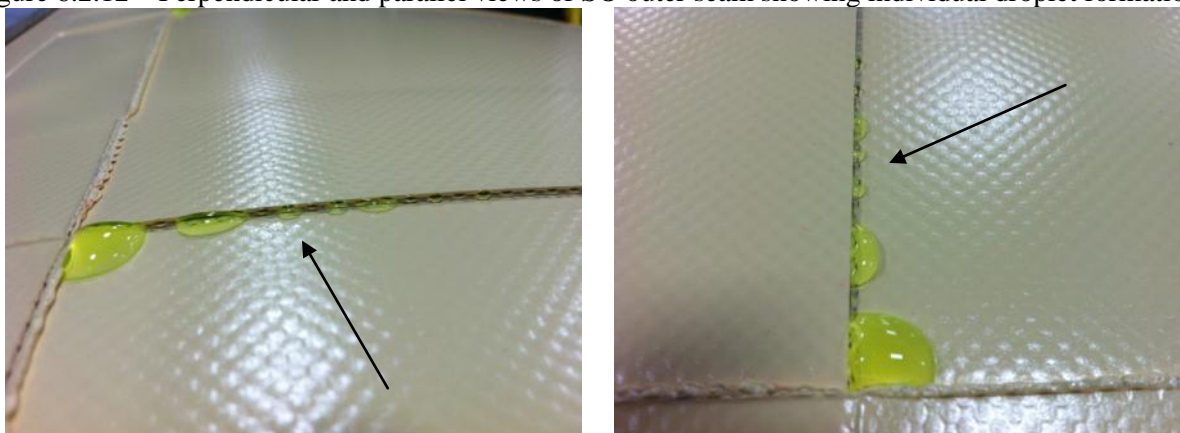
Figure 6.2.13 – Dye flow out of seam was greater at the beginning of second day once the system re-pressurized to ≥ 15 inches H_2O. The temperature was less than 90°F at the start.
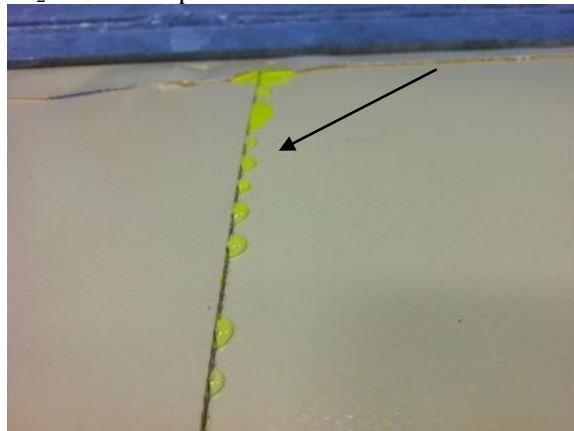
There were slight gaps where the warp panel seam and the frame intersect. The warp panel seam leaked due to inadequate compound flow during RF welding. This produced the larger droplets (also first to appear) as can be seen in the 90 degree corner in Figures 6.2.12 and 6.2.13.

As the sample cooled overnight, both the temperature and the pressure would reduce, typically from 15 inches H_2O at 140 °F, down to 5 inches H_2O at 90 °F. The dye that seeped out of the seams dried and crystalized adjacent to the seam. All three warp panel seam edges, ①, ② and ③, seeped dye and left dried residue.

Figure 6.2.14 – Dye and dried dye residue at all three seam open scrim edges ①, ② and ③
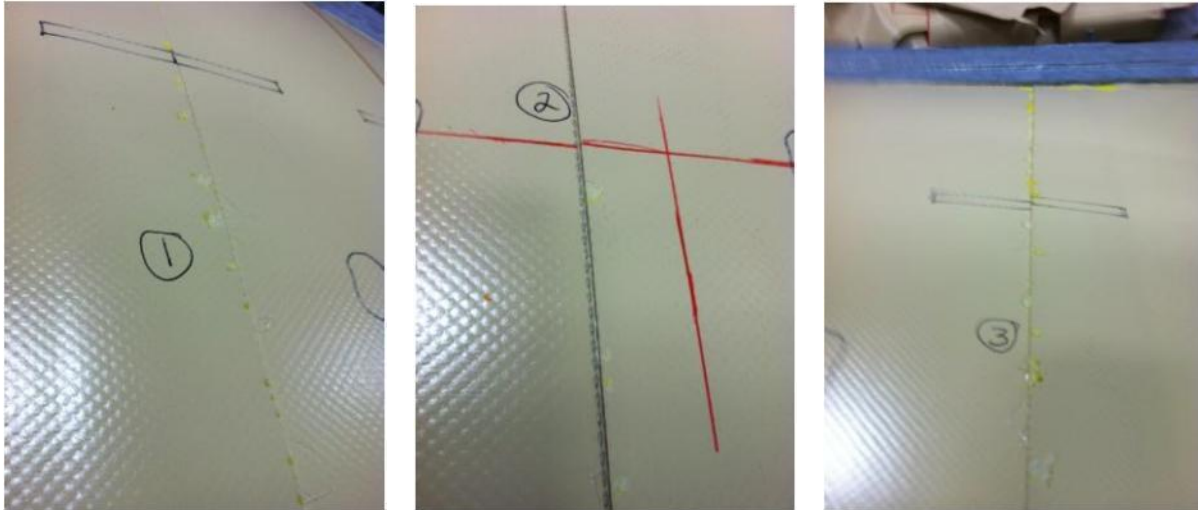
The extent of fluid penetration through the fabric becomes evident upon close up inspection of material cross sections. Cross-sectional views of panels in both the warp and fill direction show pervasive fluid and dye penetration throughout the material (Figures 6.2.15 and 6.2.16).

Figure 6.2.15 – Material cross section perpendicular to fill yarn and seam (parallel to warp yarns). Dye penetration evident in both warp and fill yarns.
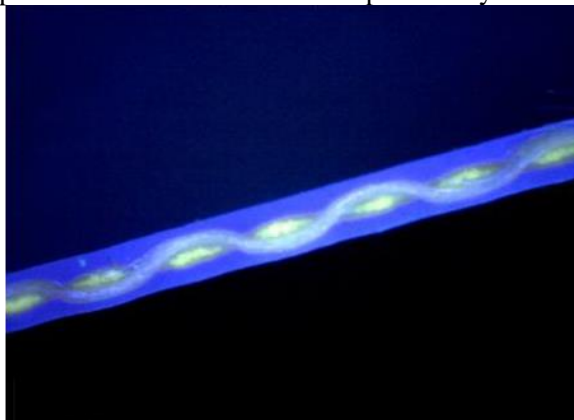
Figure 6.2.16 –Material cross section parallel to fill yarns (perpendicular to warp and seam). Dye penetration evident in warp and fill yarns.
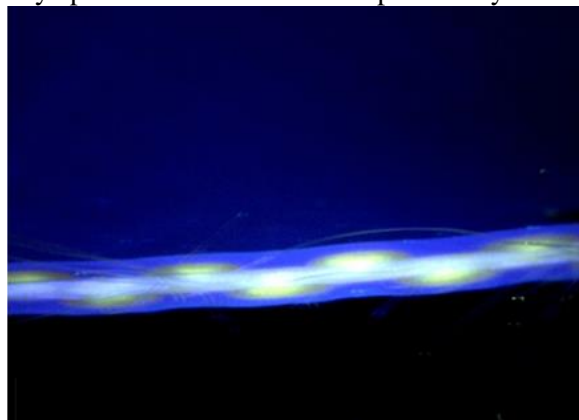
Figure 6.2.17 –Material end seam section, exterior seam, parallel to fill yarns (perpendicular to warp). Dye penetration evident in fill yarns and deposited dried dye residual from seam seeping.
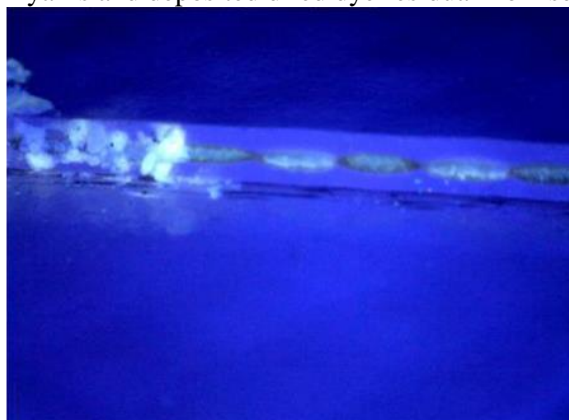
Figure 6.2.18 –Material end seam section, interior seam, parallel to fill yarns (perpendicular to warp). Dye penetration evident in fill yarns.
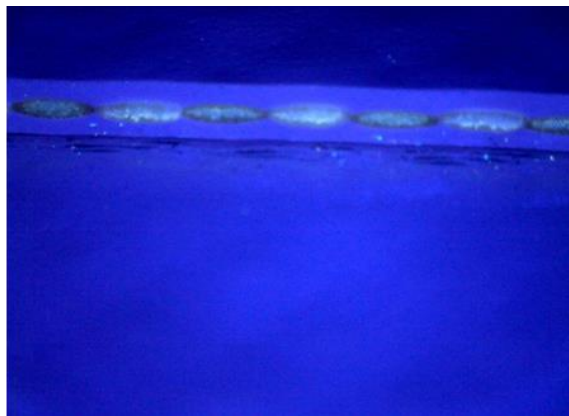
The resultant leaking that occurs out of the exterior seams can visually be traced back through the material to the open scrim at the inlet. The shingled overlap design creates an inherent interior-to-exterior material path. If the scrim is exposed, or any flaw or defect occurs in the material surface, this design increases the probability of leak formation.

6.2.3.1.2 – Centered Alternate Overlap (AO)

The alternate overlap seam staggers each alternative panel relative to the prior panel as illustrated in Section 4.2, Figure 4.2.4. Hence there are "alternating" internal and external warp panels which make up the body of the tank. This effectively "decouples" the interior to exterior material fluid pathway. If an interior panel absorbs any liquid, it still needs a flaw on its exterior for a leak to occur, since the end seams of the panel terminate under the adjoining external panel on both sides.

In addition, since the internal panel scrim is at equivalent pressure on both ends, there is no motive force for fluid transmission through the fabric. The center panel was under or interior to the two outer panels. The warp panel seams for the outer panels were above the inner panel and the outer frame. The warp panel seams for the inner panel were located beneath the two outer panels (Figure 6.2.19).

Figure 6.2.19 – AO sample picture showing <u>inner, interior panel</u> and <u>two outside, exterior panels</u>.
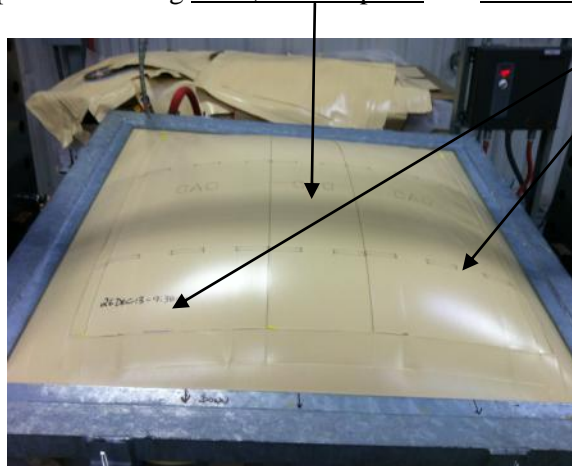
When the test was initiated and the system pressurized to ≥15 inches H_2O, leaks began to appear at the T-Seams and the upper and lower ends of the outer panel warp seams. This is shown in Figures 6.1.20 and 6.2.21.

Figure 6.2.20 – T-Seam leaks   Figure 6.2.21 – Upper end outer panel warp seam
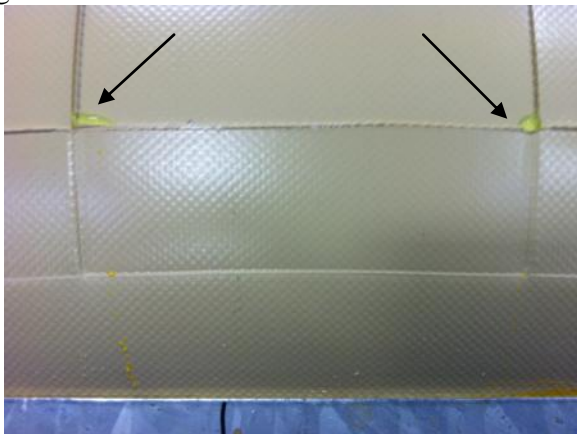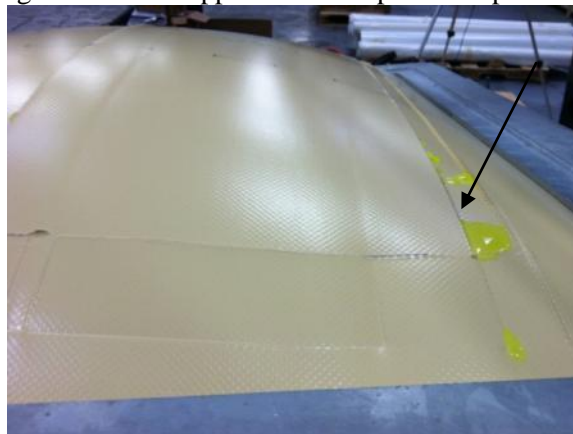
The T-Seam droplet formation was analogous to the SO sample where slight gaps, due to a lack of adequate compound flow during RF welding, created a leak path. It was noticed the second day of the test that a few droplets formed at the warp panel seam of the exterior panels above the interior panel (Figure 6.2.22). Both these droplets and the outer panel warp seams leaks were traced back to areas on the end of the warp panel where 2" scrim edges were exposed on the underside of the panel. This exposed area is a by-product of the test fixture and would not be present in an actual tank.

The dye penetrated into the outer exterior panels from this point. Most of the dye left out the outer edge (Figure 6.2.21 – closest to 2" exposure edge) while much less (a few droplets) made it to and out the center edge of the panels (Figure 6.2.22).

Figure 6.2.22 – Center panel droplets – upper and lower edge of seam
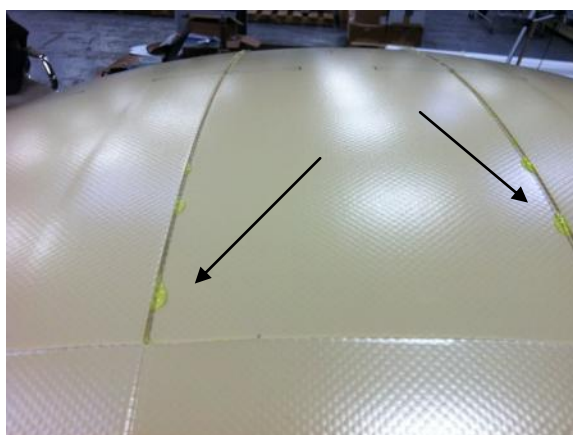
Figure 6.2.23 – Warp seam edge near lower edge – note higher dye penetration
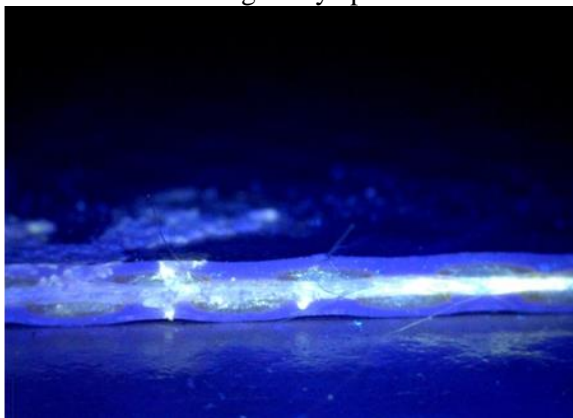
Figure 6.2.24 – Warp seam edge towards middle – note lower dye penetration
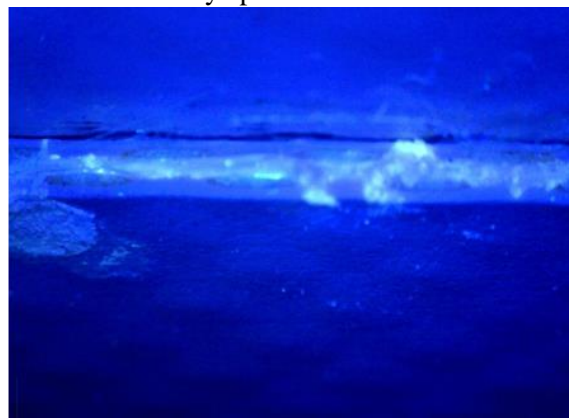
Figure 6.2.25 – Warp seam of inner, interior panel – no notable dye penetration

Figure 6.2.26 – 2" missed edge on end of warp panel Note dye penetration into warp ends on exterior panel layer (bottom) with little or no penetration on top layer (frame). This is an expected artifact that is a by-product of the test fixture.
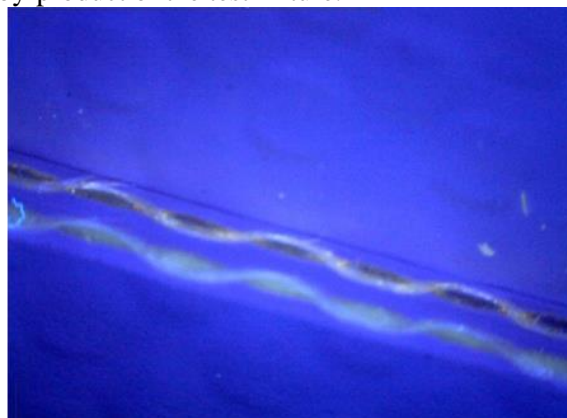
Since the interior panel is at equivalent pressure on both ends (the pressure within the tank) there is no motive force for fluid transmission through the fabric. Hence there seems to be little if any dye penetration into the central panel.

6.2.3.1.3 – Centered Single Butt Strap (SBS)

The centered single butt strap (SBS) consisted of a single 4" wide butt strap external to the adjoined 10" wide panels. The SBS was created to serve as a direct comparison to the centered double butt seam (DBS) sample, to better understand the advantages of one compared to the other. Over the course of the test, dye seeped out of the left and right-hand shingle over-lap external seam edges and in the corners of the T-Seams formed at the weld with the frame. There was some moisture present at the top and bottom of the butt seam. This was traced back to penetration through the unsealed edge located on the interior of the material frame.

In Figures 6.2.27 to 6.2.29, the sample panel is displayed as tested from the front of LTR, from left to right.

Figure 6.2.27 – Left shingle overlap seam
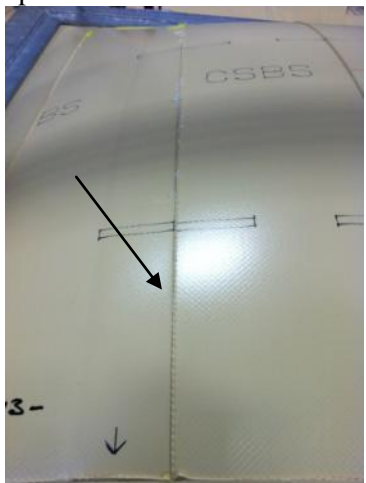
Figure 6.2.28 – Center external single butt strap seam
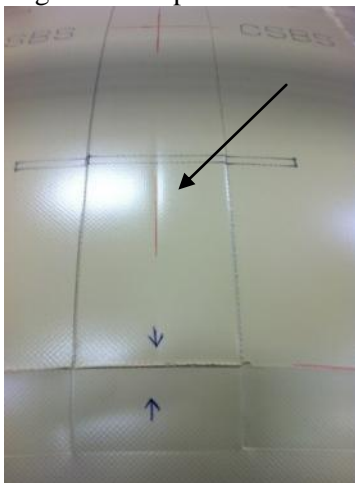

Figure 6.2.29 – Right overlap single overlap seam
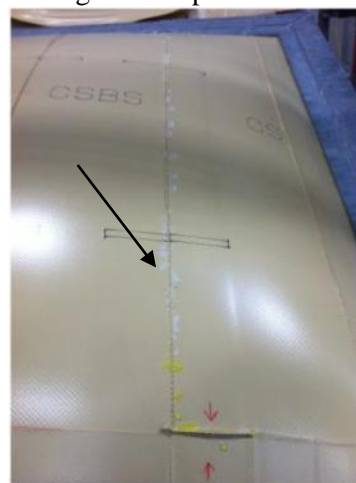
Figures 6.2.30 - 6.2.35 illustrate dye penetration across the sample, from right to left, looking at the cut section from the top. It clearly illustrates the pathway for dye penetration through the sample starting from the framed edge, through the outer panel, the inner panel and all associated overlap seams and the central single butt seam.

Figure 6.2.30 – Frame panel – no interior exposed scrim – no dye penetration
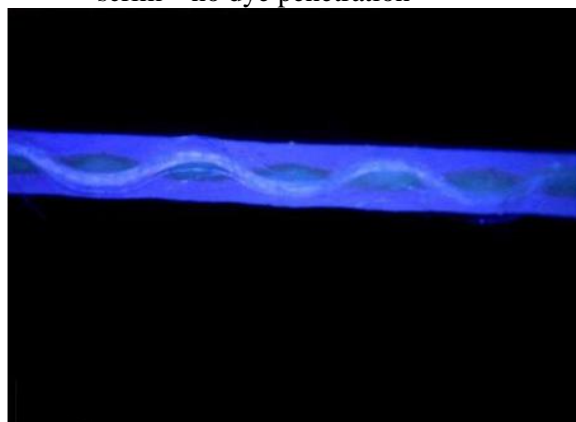
Figure 6.2.31 – Frame panel / outer panel weld – dye penetration inner side panel
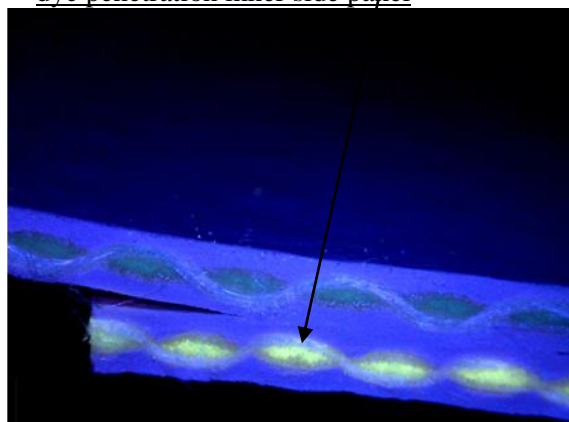
Figure 6.2.32 – Side panel middle with exposed scrim – dye penetration
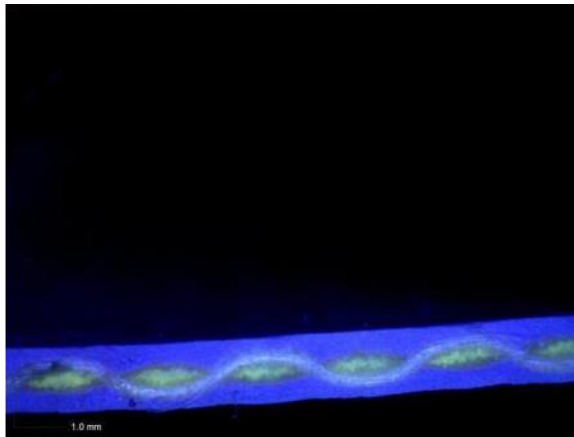
Figure 6.2.33 – Shingle overlap weld with two interior scrim exposed panels – dye penetration in both
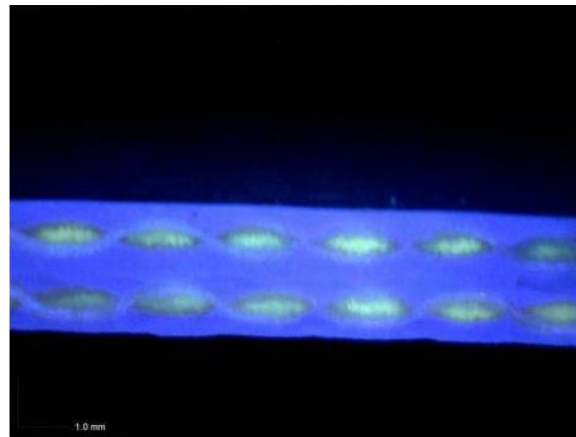
Figure 6.2.35 – Single butt seam weld (1) – <u>top butt seam showing limited dye penetration down center from exposed end;</u> dye intensity drops moving outward in the butt seam. <u>Bottom panels showing some limited penetration from open interior face (2)</u>.
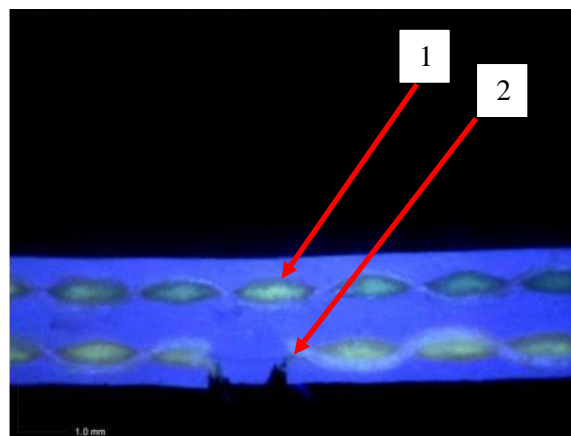
6.2.3.1.4 – Centered Double Butt Strap (DBS)

The centered double butt strap (DBS) consisted of two, 4"-wide butt straps sandwiching the adjoining 10" wide panels internally and externally. The DBS served as a direct comparison to the centered single butt seam (SBS) sample, to better understand the impact of the second internal butt strap. Like the SBS, dye seeped out of the left and right hand shingle overlap external seam edges and in the corners of the T-Seams formed at the weld with the frame. There was some moisture present at the top and bottom of the butt seam. This was traced back to penetration through the unsealed edge located on the interior of the material frame.

Figure 6.2.36 – <u>Left shingle overlap seam</u>
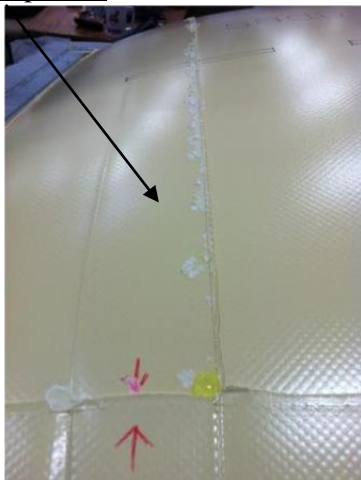
Figure 6.2.37 – <u>Center external double butt strap seam</u>
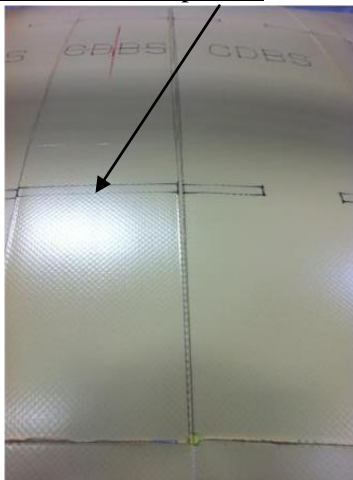
Figure 6.2.38 – <u>Right shingle overlap seam</u>
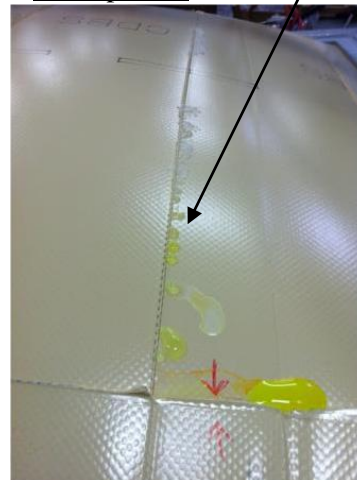
Figure 6.2.39 – External overlap weld seam
– residual dye deposition
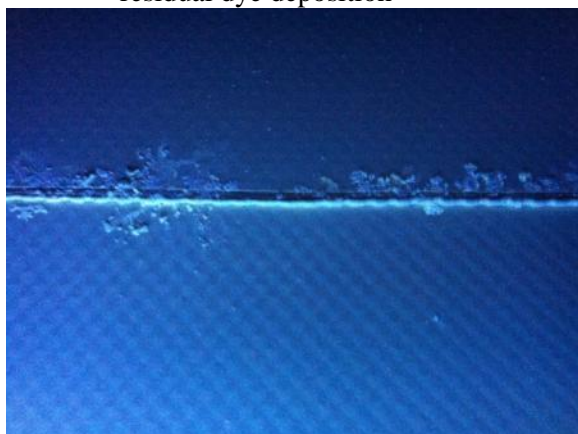
Figure 6.2.40 – Internal overlap weld seam
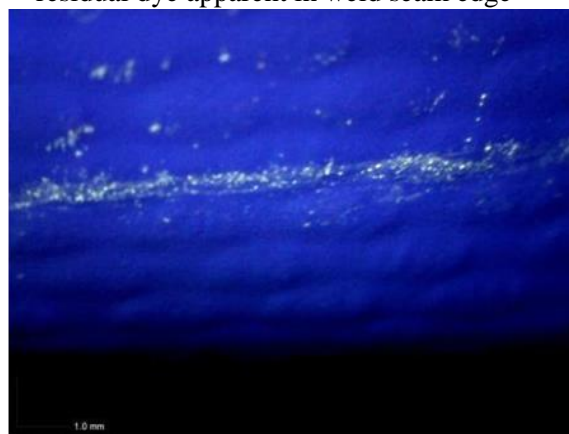– residual dye apparent in weld seam edge

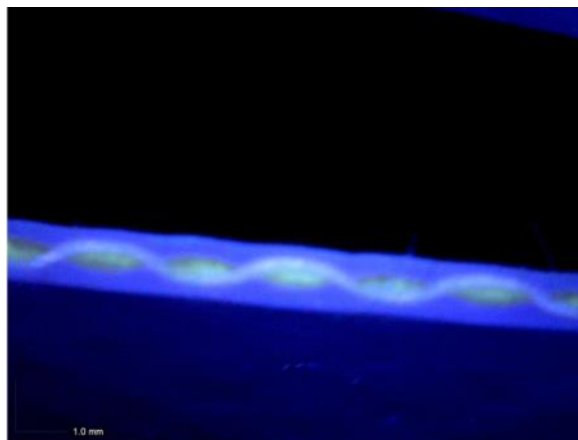Figure 6.2.41 – External panel with exposed edge dye penetration present

Figure 6.2.42 – Overlap weld seam
– dye out of external section – underlying panel with DBS on other end, minimal penetration
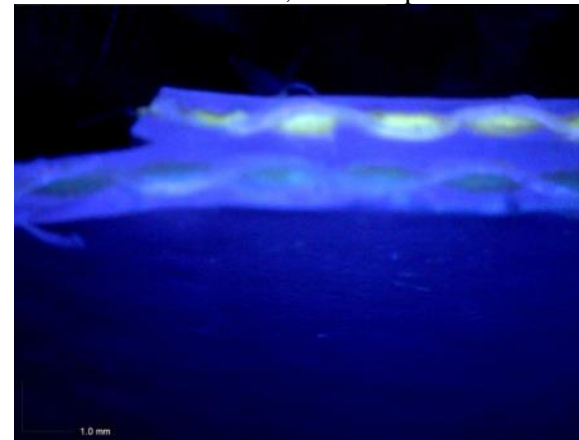
Figure 6.2.43 – Central panel ending in DBS
    – no dye penetration present
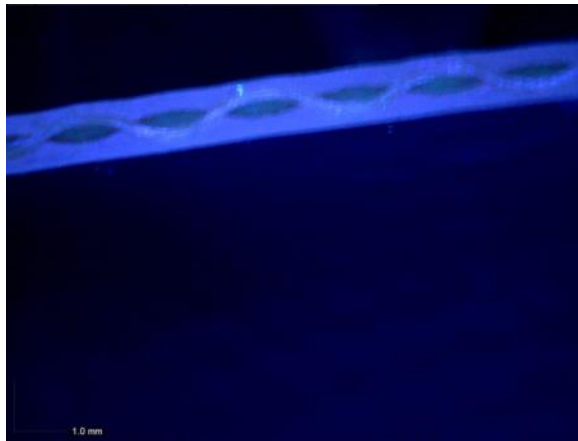
Figure 6.2.44 – Double Butt Seam cross section
– minimal dye penetration internal strap, none
apparent on center panels or exterior strap

The lack of dye penetration into the panels with a butt strapped weld illustrates the value of the second internal butt strap when compared to the SBS. Sealing the interior effectively closed the exit path for fluid flow entering through the exposed interior overlap seam on the other end of the panel.

6.2.3.2 – Panel Leaks

The focus of these tests was to damage the main body of the panel away from any seams. In most cases, his type of damage is typically the function of an external event. Examples of such events would be mishandling of the tank during deployment (dragging across a rough surface that leads to scuffs or abrasions of the exterior compound) or the inadvertent grazing of the surface during fabrication (hot air gun).

6.2.3.2.1 – Abrade 1

An initial single-ply panel was abraded on the inside near the center of the panel and 14" down the warp axis on the outside of the panel.

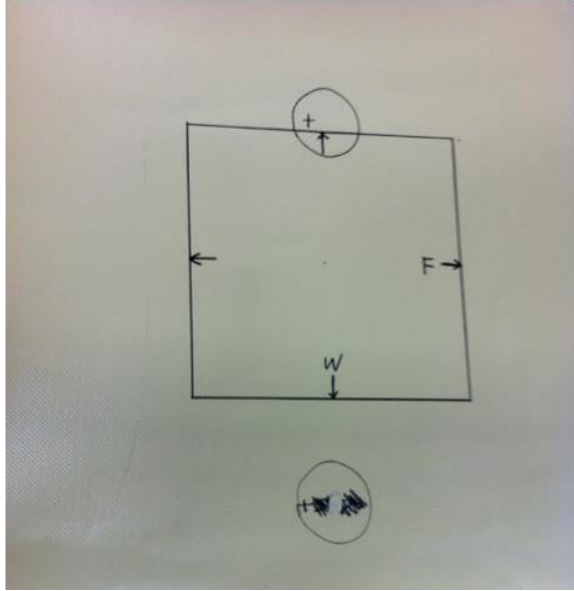Figure 6.2.45 – Location of inside (top circle) and outside (bottom circle) abrasions

Figure 6.2.46 – Drill based rotary abrasion wheel

Figure 6.2.47 – Internal surface compound removed with abrasive wheel exposing underlying scrim

Figure 6.2.47 – External surface compound removed

The initial abrade sample was run extensively for 50 hours with minimal apparent dye penetration. Dye was never seen exiting the outside abrasion of the panel 14" downstream from the inlet. Upon close review, it was suggested that the abrasion needed to be deeper than just the removal of the surface compound and the fiber bundles needed to be disrupted for fluid transfer to occur.

Figure 6.2.48 – Initial penetration of dye into fabric reducing along material axis

6.2.3.2.2 – Abrade 2

A new sample was prepped with deeper abrasions that went through the coating compound and disrupted the fiber bundles below. Like the previous test, only one spot was abraded internally at the center of the panel. Externally, however, three abrasions each were added along the fill and warp axis in line with the internal scuff. They were labeled FCF2, FCF3 and FCF4 for the scuffs in the fill direction and FCW1, FCW2 and FCF3 for the scuffs in the warp direction (Figure 6.2.49). The distance from the center to FCF2 and FCW1 was 3 inches. From FCF2 to FCF3 and FCW1 to FCW2 was also 3 inches. From FCF3 to FCF4 and FCW2 to FCW3, the distance was 4 inches. Hence from the center to the farthest scuff was 10 inches, in both the warp and the fill direction.

Figure 6.2.49 – External scuff layout for Abrade 2 sample
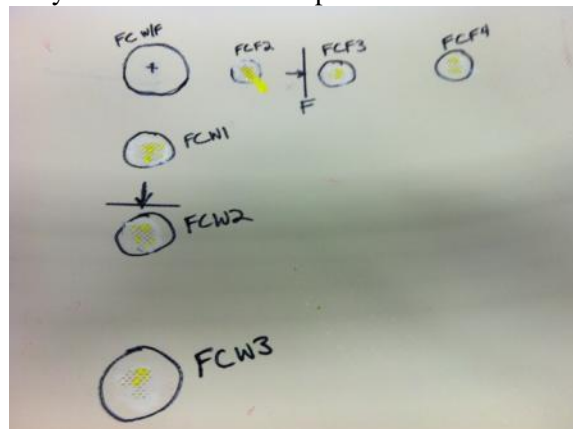
Figure 6.2.50 – Internal panel backside scuff with apparent fiber disruption

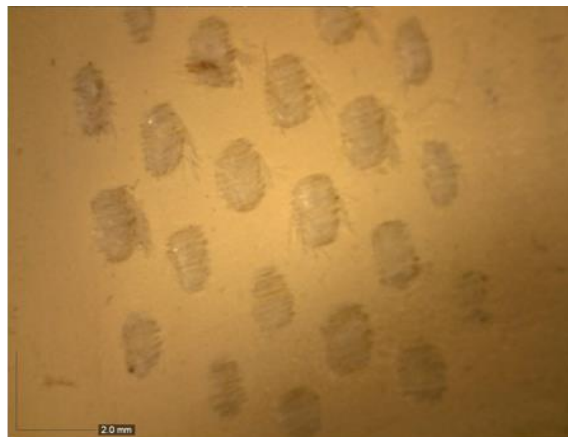Figure 6.2.51 – External panel front side FCF2 scuff

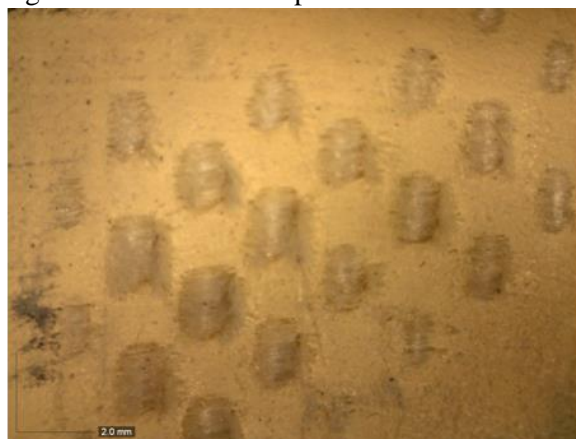Figure 6.2.52 – External panel front side FCF3

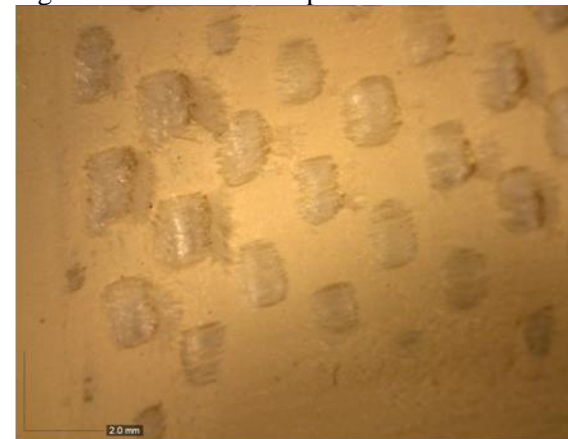Figure 6.2.53 – External panel front side FCF4
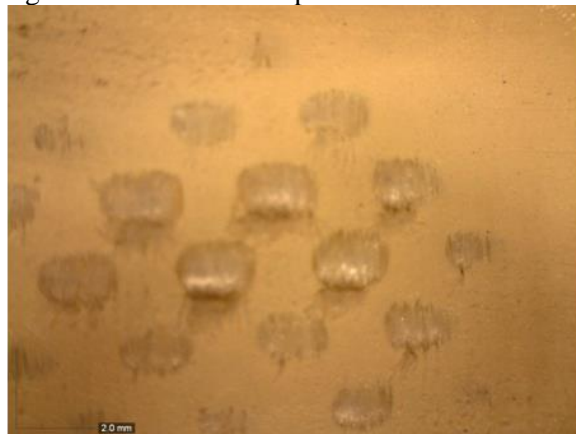

Figure 6.2.54 – External panel front side FCW1

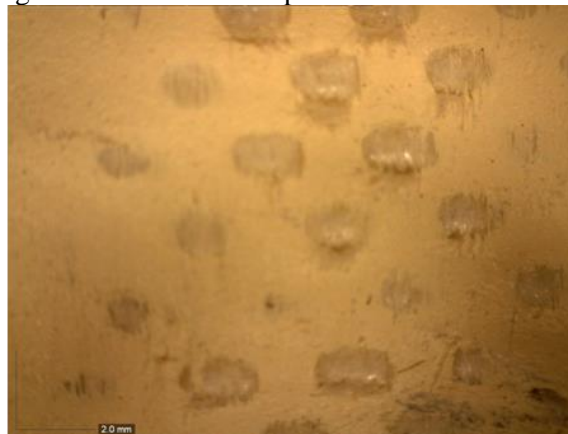Figure 6.2.55 – External panel front side FCW2
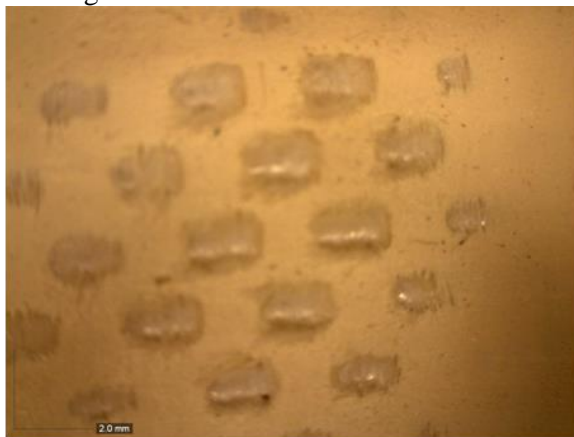
Figure 6.2.56 – External panel front side FCW3 showing

Figure 6.2.57 – Internal backside abrasion – extensive dye penetration

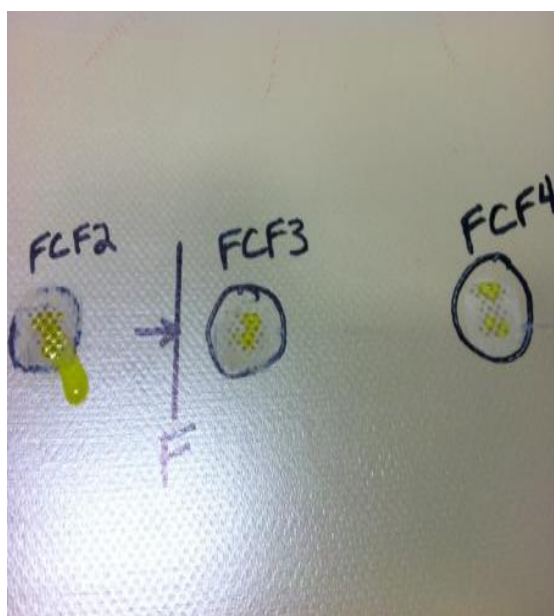Figure 6.2.58– View of FCF2-4 scuffs with dye dye seeping (FCF2) and weeping (FCF3-4)

Figure 6.2.59 – View of FCW1-3 scuffs with seeping (FCW1) and weeping (FCW2-3)
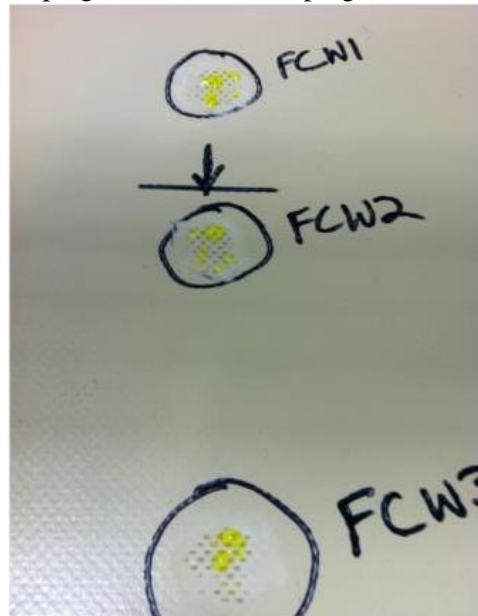
Figure 6.2.60 (next 4 pictures) – View of FCF2 leak progression from a weep (droplet formation) to a seep (repeated droplet starting to run)
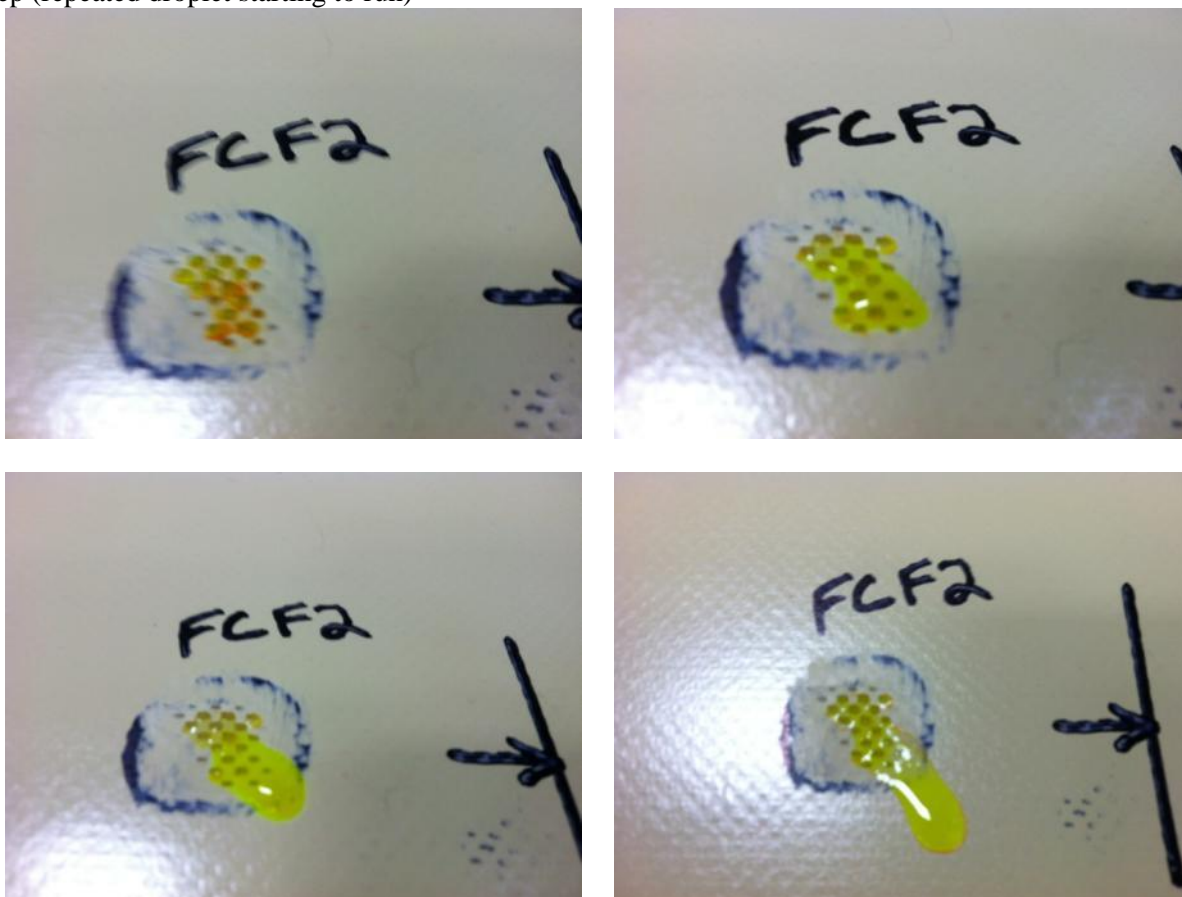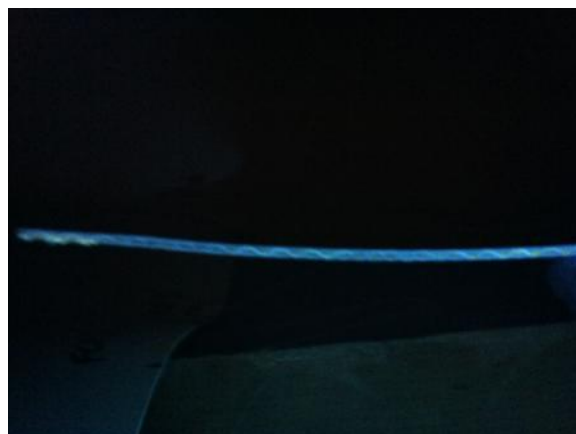

Figure 6.2.61 – View of FCW1 classic droplet formation. As droplets form out of individual fiber bundles, they combine with neighboring droplets to form a weep and then a seep.

Figure 6.2.62 – Cross-sectional view showing higher dye concentration at three areas where abrasions are located.

Unlike the first abrasion sample, it was possible in this test to induce leaking from all external scuff marks. This confirms the suggestion that fiber disruption, not just compound removal, aids in creating a leak. It took approximately 18 hours for the first droplets to appear at FCF2. The system was allowed to sit at or under 18 in H_2O for the entire day with no additional droplet formation at any of the sites. As the

temperature of the system increased, the droplets which appeared at FCF2 actually dried and the typical orange salt residue remained.

At the start of the third day, the system was filled to just over 18 in H_2O and all six of the sites started to contain droplet formation. What was exceptionally interesting was the fact that FCF2 and FCF4 seemed to have the greatest droplet formation while FCF3, which was central to FCF2 and FCF4, lagged. When reviewing the original close up abrasion pictures, it does appear that FCF3 possibly did not have as great of fiber bundle damage or broken fibers (Figures 6.2.51 – 6.2.53).

6.2.3.2.3 – Hot Air Gun

Welding the inside of a tank or tank seam as a secondary operation (e.g., adding a patch) a fabricator may use a hand held hot air gun. Working inside of a closed tank, in a confined space, the probability of accidentally "nicking" a panel or seam edge is greatly increased. To model this instance, the center of a sample panel was exposed to the corner of the tip of a BAK hot air gun welder for approximately 1-3 seconds at a temperature of 1300 °F (Figures 6.2.63 and 6.2.64).

Figure 6.2.63 – BAK Hot Air Gun

Figure 6.2.64 – Fan tip of Hot Air Gun

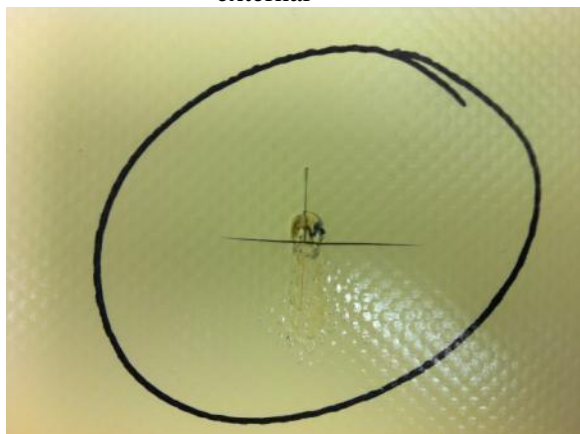Figure 6.2.65 – Hot air gun tip corner imprint – external

Figure 6.2.66 – Hot air gun tip corner imprint – internal

Figure 6.2.67 – Hot air gun tip corner imprint – external close up – note secondary compound pitting (right) caused by peripheral hot air flow
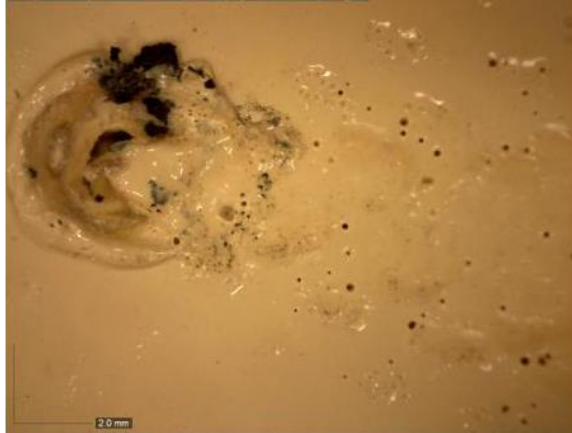
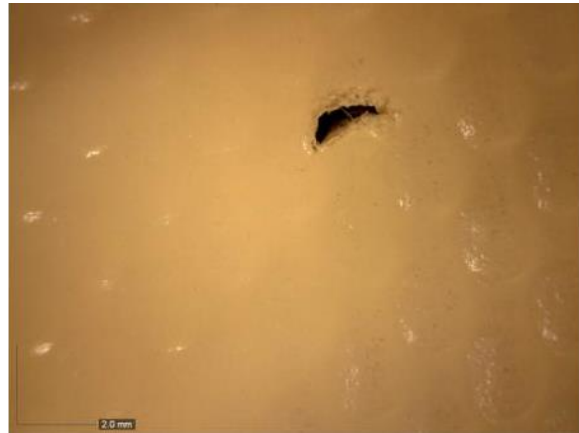Figure 6.2.68 – Hot air gun tip corner imprint – internal – close up

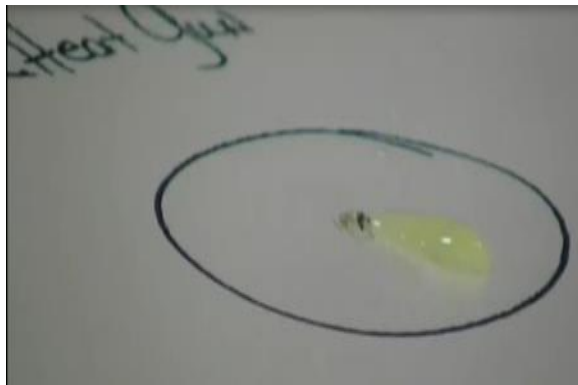Figure 6.2.69 – Immediate Class II seep upon initial fill

Figure 6.2.70 – At pressure of 15 in H$_2$O, leak became profuse
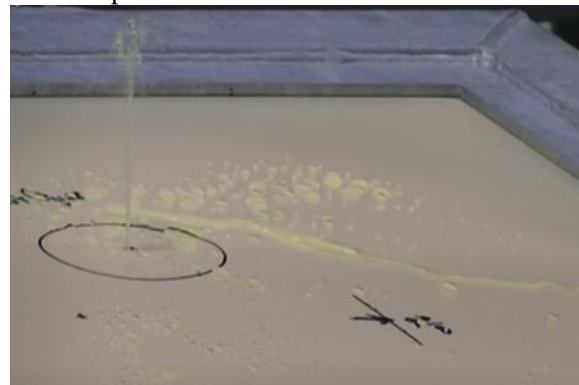
Figure 6.2.71 – Cross-sectional cut and view with black light – little if any dye penetration
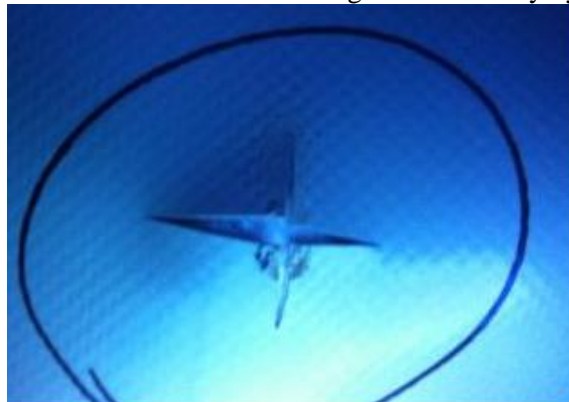
This test clearly illustrated that secondary welding operations should be avoided whenever possible or adequate quality controls governing their use must be followed. Performing the forensics of tanks that were tested at SwRI numerous hot air misses or excessive compound flow were evident on the interior of the tank due to both primary and secondary welding operations (Section 5.4.5.4).

For this sample, the excessive damage created by a momentary 1-3 second lapse caused a catastrophic failure condition. The test needed to be aborted prematurely (less than 2 hours) since chamber pressure

could not be maintained and it was necessary to shut down to protect the pump. Heat was never applied during this test. Instead, the pump was run at ambient temperature. The clear pathway from the inside to the outside of the panel, paired with the lack of time for exposure, presented a minimal opportunity for dye penetration into the material (Figure 6.2.69).

6.2.3.2.4 – 50-lb Fold and Compress

Tanks are folded and compressed when they are packed for shipping and remain in this state while they are stored. It is believed that issues arise only when the storage and shipping conditions exceed those recommended for the material (tested in accordance with MIL-PRF-32233).

A test was run to verify the condition of material that had been folded and compressed. The sample was folded in half along the warp thread direction and then in half along the fill direction to produce a folded corner in the middle of the panel. A 50-lb weight compressed the corner over a 24-hour period at room temperature to see if it had any impact on material integrity. Through microscopic visual inspection, it was determined that folding and compression alone may have slightly creased the material but did not breach or crack the coated fabric. Based on previous experience, testing was suspended since it was determined that exposure in the LTR would not produce a leak.

For future consideration, it may be worthwhile to repeat this test at extreme temperature conditions close to the acceptable limits for an extended period of time.

Figure 6.2.72 – External overall fold and compress

Figure 6.2.73 – Close up of external fold and compress

Figure 6.2.74 – Close up of internal fold and compress

6.2.3.2.5 – MEK / THF + Fold and Compress

Tank fabricators and tank customers typically use chemicals to clean or prepare a surface for welding or repair. Seaman 1940 MS 337 PTFF and other polyurethane tank materials all have information published recommending acceptable chemistries for cleaning or preparing the surface. Evaluation of past samples from the field has indicated that, on occasion, cleaning chemistries other than those recommended may have been used. Historically, the use of both methyl ethyl ketone (MEK) and tetrahydrofuran (THF) is known since they are commonly available cleaning solvents. However, they are not recommended for use with Seaman Corporation's polyurethane tank material. For recommendations on material care for Seaman 1940 MS 337 PTFF, either the FY2008 report may be referenced or Seaman Corporation contacted. For any tank material, the material manufacturer should be contacted regarding compatible cleaning chemistries prior to use.

While preparing the sample for this test, the material was folded twice to give a corner edge. MEK was then applied by dabbing it on the folded corner with a saturated soft cloth and allowed to dry. After a couple of applications with the MEK the surface was inspected with a magnifying glass. It was noted that it had no visible impact on the material's coating. It was decided to then try THF on the same folded corner. After one application with the THF, cracks appeared in the material coating. THF was applied on both an internal and an external corner fold in the approximate center of the panel.

Figure 6.2.75 – External face of MEK / THF treated sample

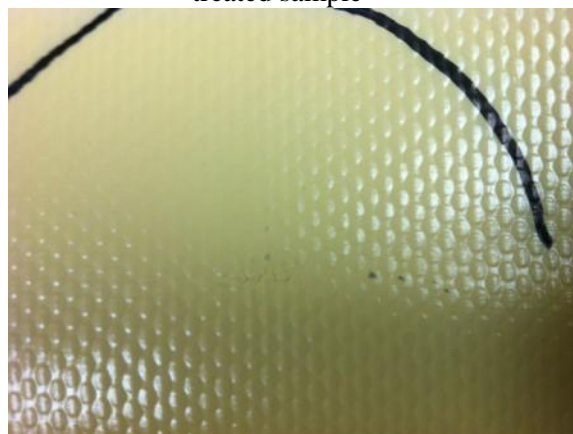Figure 6.2.76 – Internal face of MEK / THF treated sample

Figure 6.2.77 – Close up internal face showing
compound cracking

Figure 6.2.78 – Close up internal face showing
additional area of compound removal
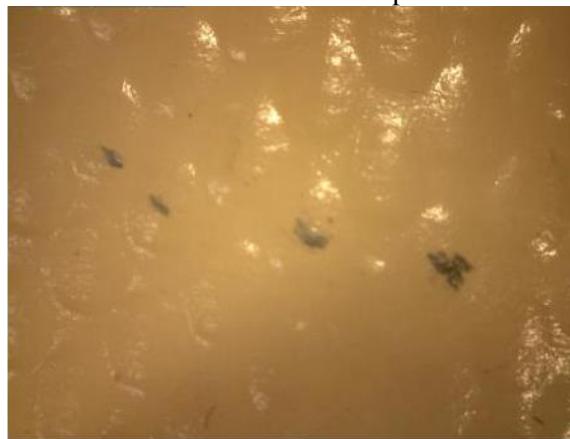
Figure 6.2.79 – Close up of external face showing compound cracking

Figure 6.2.80 – Weep produced at beginning of
second day of testing, right after reaching pressure

Figure 6.2.81 – Cross-sectional cut with
black light showing some dye penetration into
the material at corners of cut

The test was run over the course of two days. A weep was produced at the beginning of the second day after the system was brought back up to pressure. The weep formed and began to dry out as the temperature increased. It never exceeded a weep, by definition, and never turned into a seep.

6.2.3.2.6 – Pinholes

The sample was prepared with a series of five pinholes (~0.20 inch diameter) in the back center of the panel (Figure 6.2.82). The pinholes punctured the back side coating into the fiber without breaching the front coating face. First three pinholes were placed in adjacent fill fiber rows. To the right and left side of the bottom pinhole, two additional pinholes were placed in adjacent warp fiber bundles (Figure 6.2.83). Externally, three pinholes each were added along the fill and warp axis in line with the internal pinhole fiber bundles (Figure 6.2.84). They were labeled FCF1, FCF2 and FCF3 in the fill direction (Figure 6.2.85) and FCW1, FCW2 and FCF3 in the warp direction (Figure 6.2.86). The distance from the center (FCF1/W1) to FCF2 and FCW2 was 3 inches. From FCF2 to FCF3 and FCW2 to FCW3 was 6 inches. Hence from the center to the farthest pinhole was 9 inches, in both the warp and the fill direction.

Figure 6.2.82 – Back center of panel

Figure 6.2.83 – Back center hole locations (warp and fill)
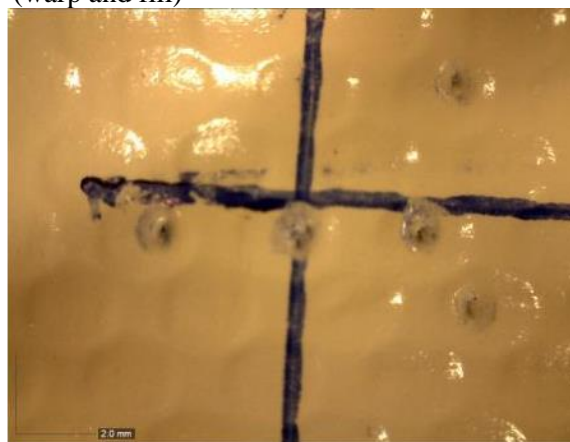

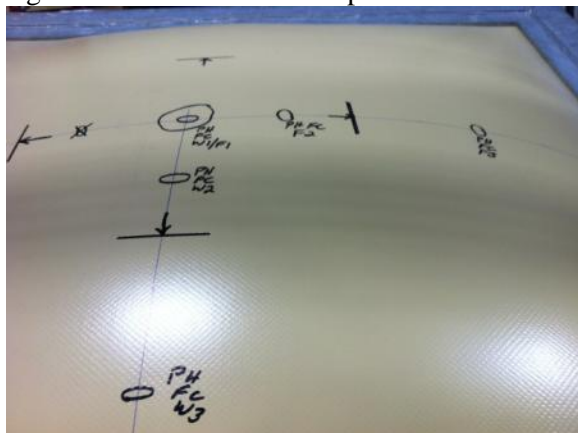
Figure 6.2.84 – Front face of panel

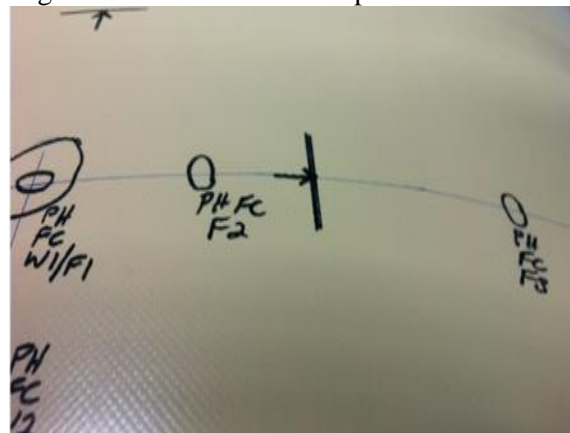Figure 6.2.85 - Fill direction pinhole locations

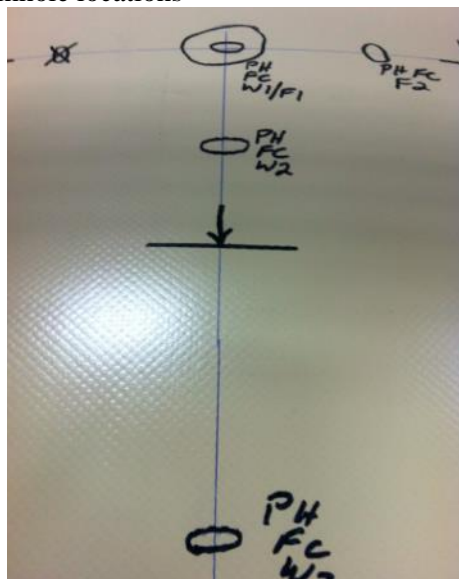Figure 6.2.86 – Warp direction pinhole locations

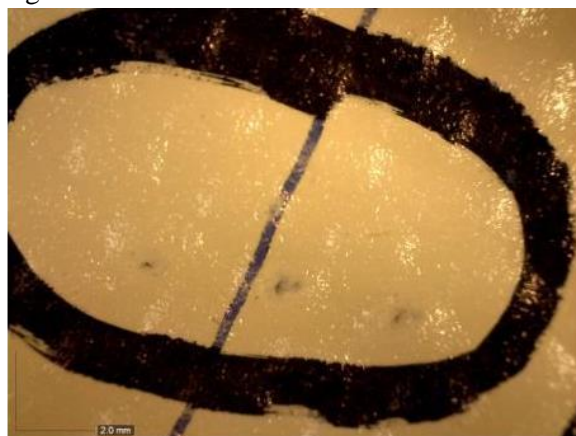Figure 6.2.87 – Fill direction FCF3 location
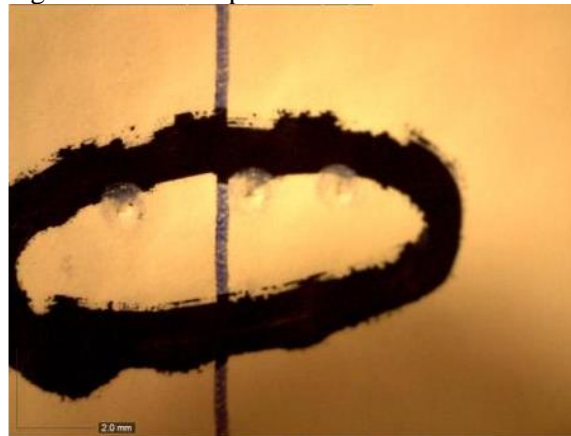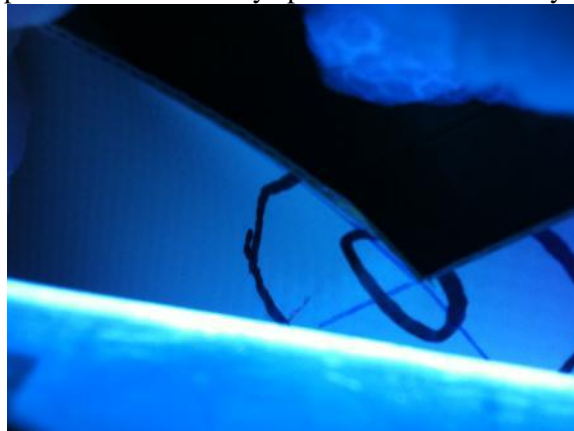

Figure 6.2.88–Warp direction FCW3 location

Figure 6.2.89 – Cut through pinholes – minimal dye penetration visible only near inlet backside holes

Throughout the 43 hours of testing, there were no visible fluid transfer to or droplet appearance at the outside pinholes. Minimal dye penetration was evident at the interior backside pinholes and no visible fluid transfer through the scrim.

6.2.3.3 – Fittings

When the tank farm went on line at SwRI, it was noted that a number of tanks were leaking at the base of the manway / discharge fitting. Upon checking these tanks with a torque wrench, it was noticed that most that leaked were well under the fabricators specified torque recommendation of 10 ft-lbs. All of the loose bolts were re-torqued and the leaks were either eliminated or minimized. All of the loose fittings were supplied by one manufacturer. The bolts may not have been adequately torqued when the inside of the tank was dried after the water leak test or they worked their way loose during shipping, deployment or expansion in the Texas sun.

Based on this field experience, it was decided to test a number of manway / discharge fitting designs to see what could be learned. A standard fitting set from each of the two fabricators were tested as shipped. In addition, the O-Ring compression fitting was tested to determine if it offered any advantages over the standard fittings. To make sure all the air was removed from under the manway fitting, it was necessary to drill a hole in the cap and add a secondary air removal tube (Figure 6.2.90).

6.2.3.3.1 – Standard Tank Manway / Discharge Fitting

The tank manway was selected since it represented tanks which had loose fittings at the field site. Upon checking with a torque wrench, it was verified that all the bolts were under specification. For the test, the left side of the fitting, the bolts labeled 11-20 were left at < 5 ft-lbs. For the right side of the fitting, the bolts labeled 1-10 were all set with the torque wrench to exactly 5 ft-lbs. Through the first 18 hours of the test (6 hours heating / 12 hours cooling), no leaks appeared. At this point, bolts 1-6 and 10-20 were tightened to 15 ft-lbs and bolts 7-9 were loosened until a 1 mm gap was visible between the bottom of the bolt head and washer. For the next hour and a half, the test proceeded with no leaks visible.

At this point, bolts 5-10 were loosened until a 2 mm gap was present. Leaks then started to appear between bolts 7-9. The leaks came out of the bolt-hole in the plate and from under the cork gasket against the material.

Figure 6.2.90 – Tank fitting showing additional   Figure 6.2.91 – Tank fitting – side view
air purge tube out of fitting cap

Figure 6.2.92 – Bolts 7-9 loosened with a 1 mm gap
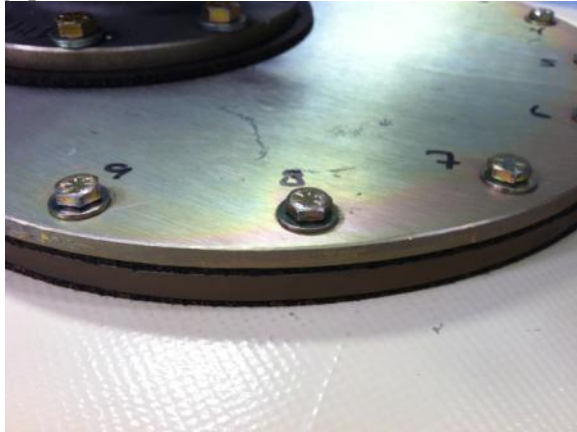

Figure 6.2.93 – Bolts 7-9 with leaks coming out of bolt-holes and from under the cork gasket
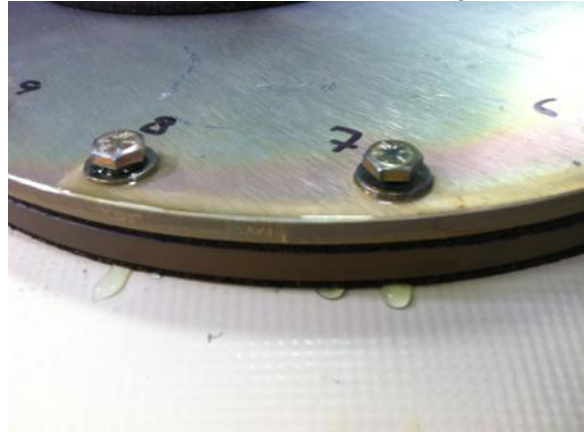

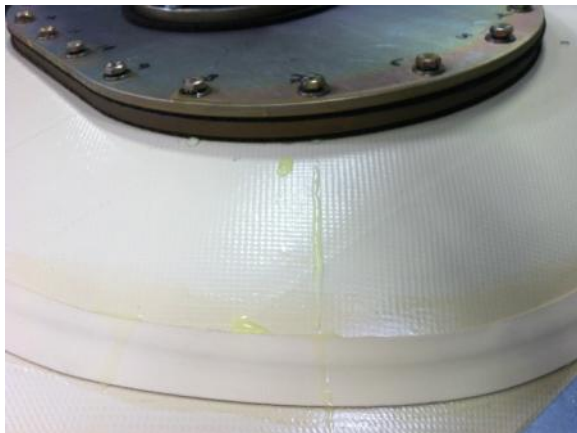Figure 6.2.94 – Seep occurring from bolts 7-9

Figure 6.2.95 – Bolt-hole 7 under black light with slight dye penetration in scrim around perimeter
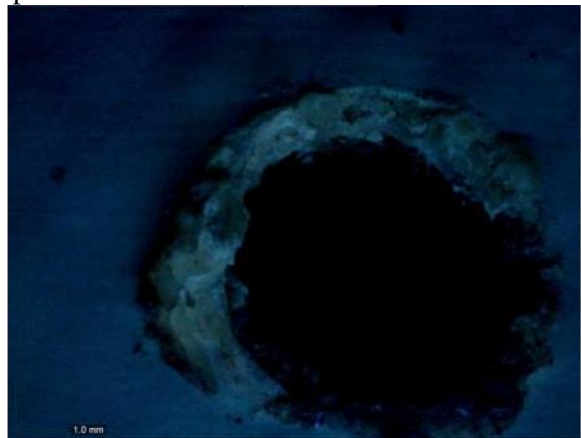
Figure 6.2.96 – Dye penetration in material scrim for bolt-hole 7

Figure 6.2.96 shows directional dye penetration from the bolt-hole outward through the scrim and around the bolt-hole perimeter. By comparison, the dye does not seem to penetrate inward for the bolt-hole. In addition, loose manway bolts may allow the holes in the material to stretch into elongated slots over time.

6.2.3.3.2 – Standard Tank Manway / Discharge Fitting

This tank manway was selected since it was representative of tanks which did not have loose fitting issues at the field site. Upon checking with a torque wrench, it was verified that all of the bolts (1-20) were over the 10 ft-lb specification, as shipped. The test ran for almost 42 hours (13 heated) without evidence of any leakage. It was concluded on the third day without leaks.

Figure 6.2.97 – Tank manway fitting   Figure 6.2.98 – Tank manway fitting close-up
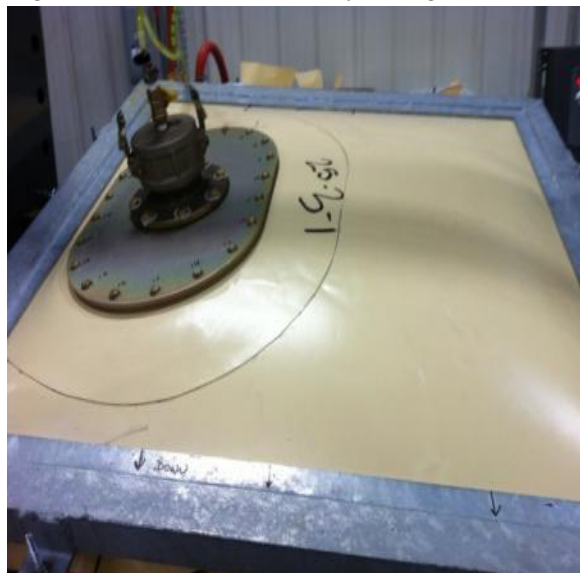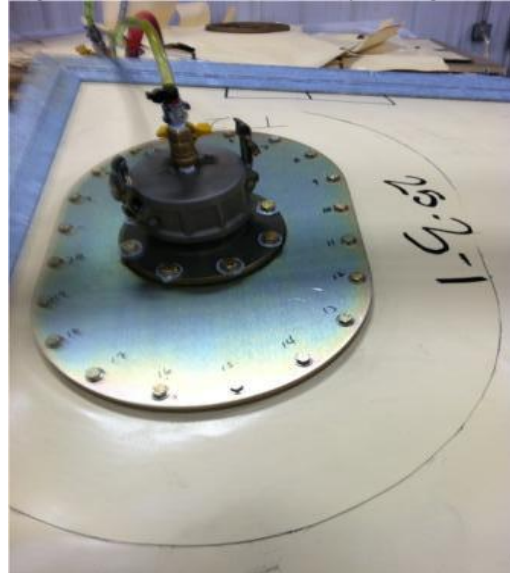
6.2.3.3.3 – O-Ring Compression Manway / Discharge fitting

This tank manway was selected for study because it contained the alternate O-ring compression manway / discharge fitting. This design includes an additional lower 50 durometer O-ring on the inner ring of the access door fitting (per Mil-T-52983G) which isolates the bolt holes in the peripheral scrim from the fuel (Figures 6.2.99 to 6.2.100).

Upon checking with a torque wrench, it was verified that all of the bolts (1-20) were over the 10 ft-lb specification, as shipped.

Figure 6.2.99 – Tank 28 O-ring compression
exploded fitting stack-up
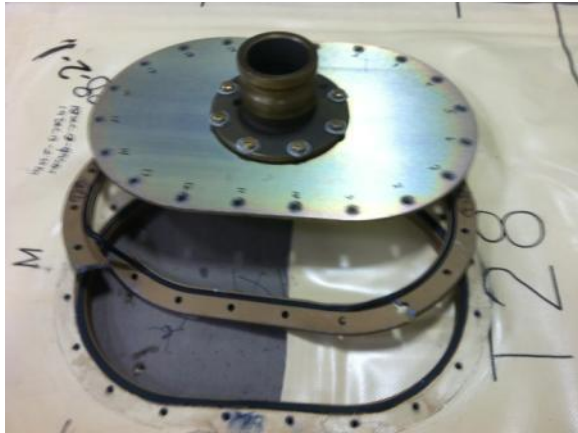
Figure 6.2.100 – Close up of additional 50
durometer O-ring isolating peripheral scrim and
bolt-holes from fluid path

The test ran for 24 hours (10 heated) without evidence of any leakage. After 24 hours, bolts 13-15 were loosened to 2mm gap, and allowed to sit for one hour with no leaks noted. Bolts 12, 16-17 were then loosened to 2mm gap and allowed to sit for an additional three hours with no leaks noted. Bolts 11 and 18 were then loosened to 2mm and a seep leak out of bolt hole 15 occurred. The stream out of 15 came out of the bottom between fabric and ring not out of the top of the bolt like it had with the standard Tank fitting. After 30 minutes with no additional leakage, the test was shut down.

Figure 6.2.101 – Tank fitting with bolts 12-15
loosened – no leak
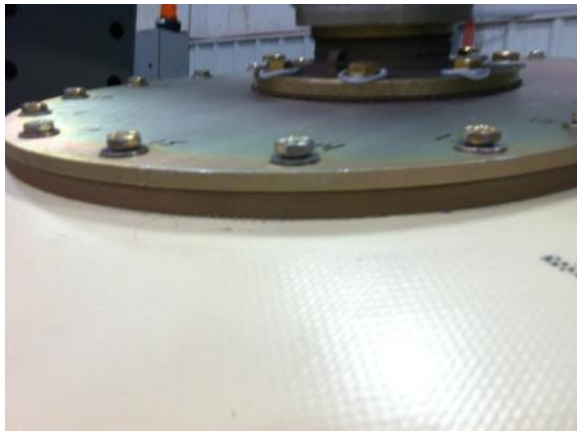
Figure 6.2.102 –Tank fitting with bolts 12-19
loosened
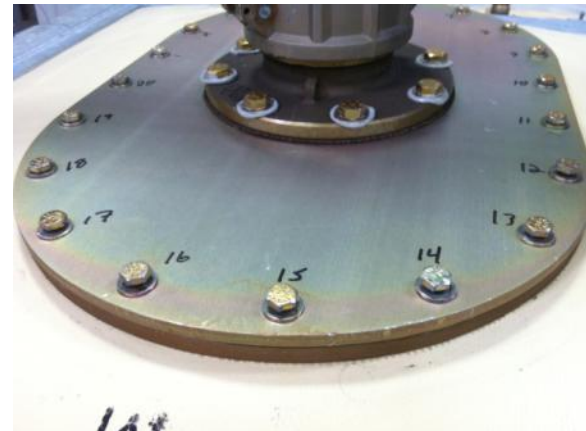
Figure 6.2.103 – Tank fitting with seep trickling out from bolt-hole 15

Figure 6.2.104 – Close up black light of bolt-hole 15 with no apparent dye penetration in scrim

Figure 6.2.105 – Cross-sectional cut of bolt hole 15 under black light showing no apparent dye penetration into scrim

The lack of flow out of bolt-hole 15, paired with the lack of dye penetration into the surrounding scrim, infers that the compression O-ring worked as designed. In addition, it took loosening additional bolts and backing the bolts off farther from the plate to create a leak over the course of four hours. This leads one to believe that the lower durometer O-ring expanded to fill the opening to some extent until a leak path was established under the external ring and gasket. Again, there was no leakage out of the top of the bolt-hole; indicating that the O-ring successfully isolated the fluid path from the material.

6.2.3.4 – Seam Tape

Seam tape is utilized to seal the open scrim edge of the polyurethane fabric when fabricating a collapsible fuel tank. For this program, three new unique seam tapes were evaluated in the field. Two of the tapes were reinforced with greige good webbing. The third, referred to as the 1" reinforced profile tape, consisted of a 1" reinforced tape with and ½"wide x 0.060" high stepped polyurethane strip to seal the step down edge of the seam. Tank samples containing the three different tapes were evaluated on the LTR by loosening under the tape or cutting through it if it were not possible to loosen without introducing further damage. An interior path also needed to be opened to allow flow to occur on an exterior seam tape breach. The seam tape samples were all cut from actual tanks with the seam tape in running vertically

down the center of the panel. The samples were then welded into a material frame to allow for sealing in the LTR. This left the outer perimeter exposed scrim of the sample exposed to the fluid in the LTR.

6.2.3.4.1 –1 Inch Reinforced Tape (1"RT)

For the 1"RT tape test, the tape was cut externally just above the center of the panel and a tape lift was created just below. After the test was concluded, it was determined that, while creating the tape lift, the probe breached the interior of the panel.

Figure 6.2.106 – Overall panel showing location of tape cut (above) and lift (below) center
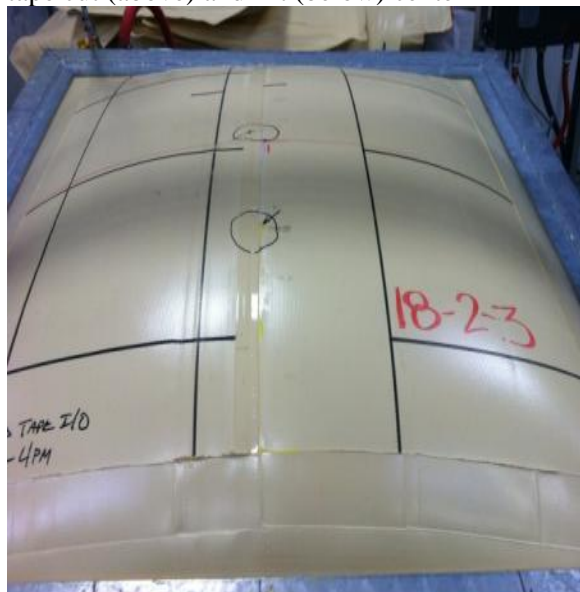
Figure 6.2.107 – Seep formation occurring at location of tape lift
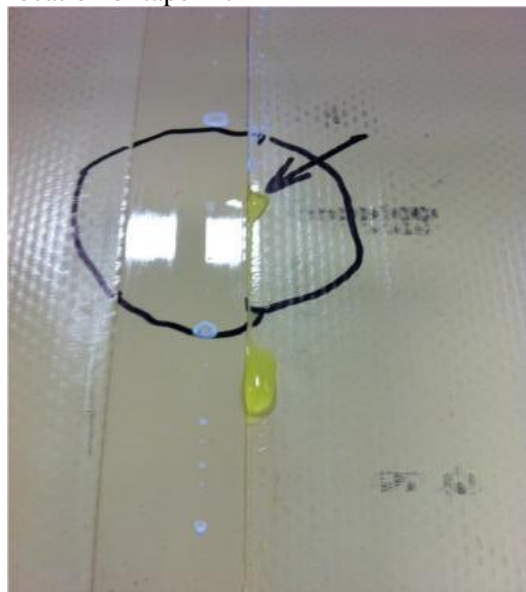
Figure 6.2.108 – Backside of tape lift indicating of breach in compound (on left)

Figure 6.2.109 – External tape cut above center panel showing milky colored deposit from very slow weep
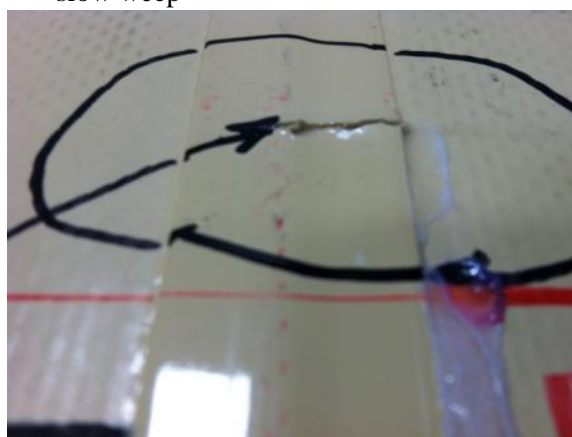
Figure 6.2.110 – Minor weeping at frame edge through un-taped scrim edge

The internal compound breach invalidated the tape lift site as a true tape lift. The seep which was produced was more of a direct path from the interior compound breach directly to the lifted tape and out. The tape cut, however, proved to be unique. There never was a clear droplet formation, weep or seep formed. However a milky residual film built up over time, suggesting that a single fiber bundle was exposed, allowing minimal flow of moisture out of the tape cut without dye making it through.

6.2.3.4.2 –2 Inch Reinforced Tape (2"RT)

For the 2"RT tape test, the tape was cut in two locations externally, vertically along a seam just above the center of the panel and horizontally across the tape about a third of the way from the bottom. An additional internal tape lift was tried. However, it was necessary to pass through heavy adhesive compound that had been applied by the fabricator (Figure 6.2.111). This created an unplanned external compound breach near the top third of the panel (Figure 6.2.112).

Figure 6.2.111 – Internal tape lift through heavy   Figure 6.2.112 – Resultant external
adhesive compound   compound breach

Figure 6.2.113 – External compound breach with dye seeping out
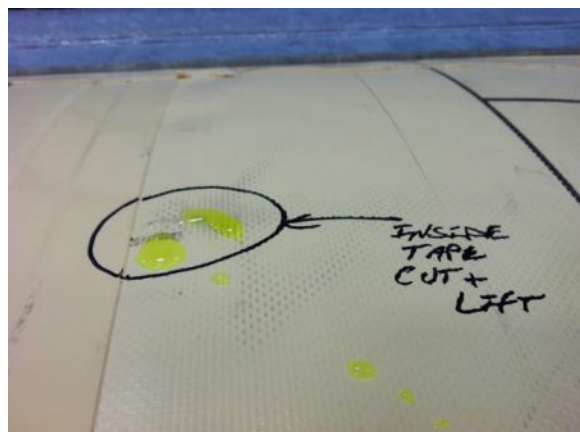
Figure 6.2.114 – External vertical tape cut with colorless droplet formation

Figure 6.2.115 – Black light close up of vertical tape cut with no evidence of dye penetration
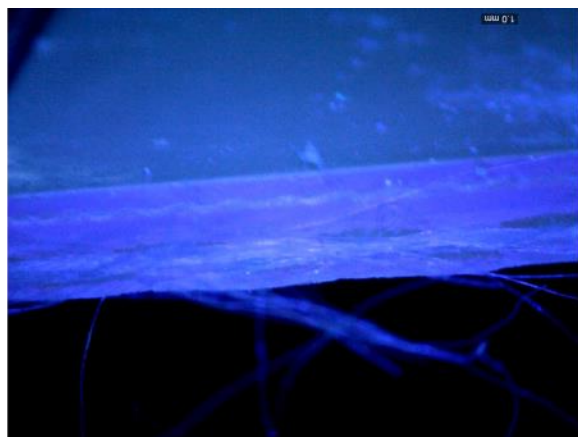
Figure 6.2.116 – External horizontal tape cut with colorless droplet formation
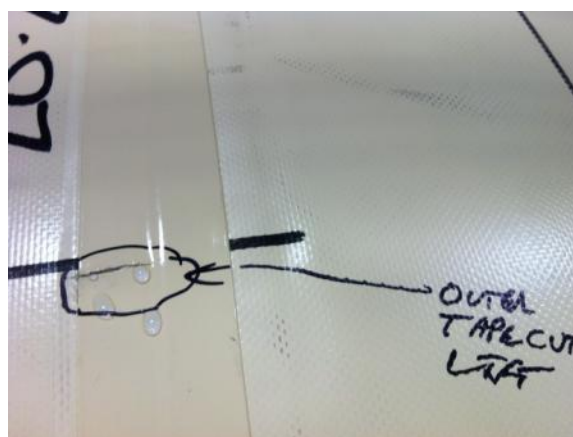
Figure 6.2.117 – Black light close up of horizontal tape cut with no evidence of dye penetration
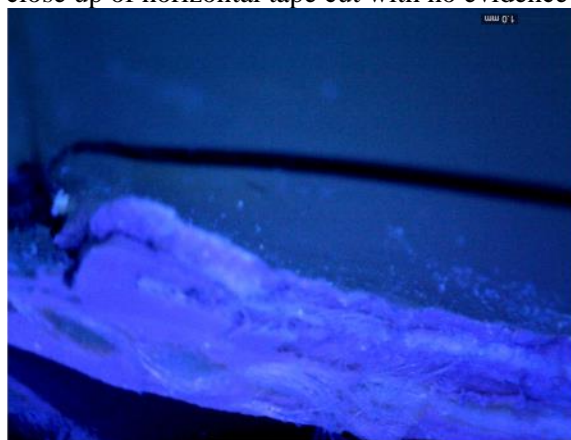
The colorless droplet formation might lead one to believe that the fluid flow was restricted and perhaps impeded by the limited flow path. The panel width was 14-16 inches wide from the potential fluid source.

In addition, the tape cuts perhaps limited the number of exposed fibers thereby further limiting the flow. In turn, this may have caused the dye molecules to stall in the fabric and not make it out of the tape breach.

6.2.3.4.3 –1-Inch Profile Tape (1"PT)

For the 1" profile tape test, both the profile and the non-profile edges of the tape were lifted internally and externally. In the first pass of introducing the tape lift on the profile side, the probe passed through the interior compound layer creating an unintentional direct leak path. A second profile side tape lift was then created above the first. For both the profile and non-profile tape lifts, an adjoining internal tape lift was created roughly 1" above the external.

Figure 6.2.118 – Tape lift profile side + thru hole
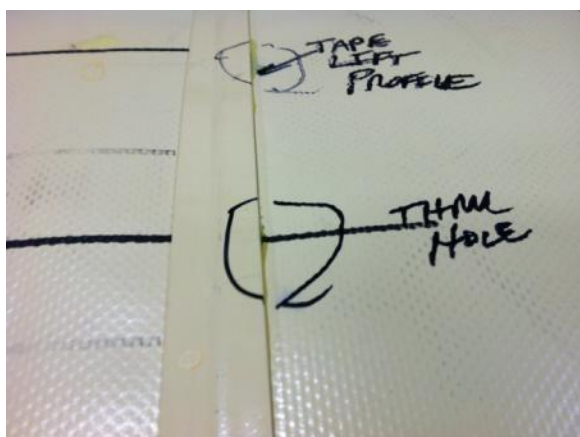
Figure 6.2.119 – Clear weep from profile tape lift side and continuous dye seep from thru hole

Figure 6.2.120 – Clear weep from non-profile tape lift side
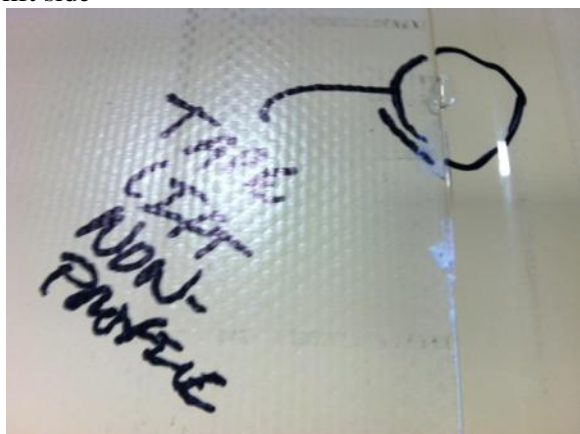
Figure 6.2.121 – Residual flow form thru hole (right of seam) and scrim edge (left)

The results of this test were consistent with the previous tape test. Wherever a tape cut or lift occurred, dye penetration and passage did not occur. Instead, a clear affluent discharge appeared. Since no dye penetration was found in the cross sectional areas where clear affluent appeared, it is assumed the fiber bundles reduced potential dye passage at the molecular level since all three tests ran for a minimum of 23 hours.

6.2.3.5 – Pressure / Temperature Impact Studies – 0.013 and 0.75 inch diameter pinholes

Throughout the LTR sample testing, pressure appeared to have a greater impact on contributing to leaks than did temperature. A leak typically would worsen and proliferate when chamber peak pressure was reached, especially after one cycle of heating and cooling. With the exception of samples with major leak sources (e.g., Hot Air Gun – 6.2.3.2.3, pg. 114), leaks would be at greatest when refilling the chamber at the start of the second day of testing. During the first day, the temperature would increase until the target of 140 °F was reached and held there throughout the remainder of the day. The chamber also would be topped off (filled) at the end of the day at the maximum pressure (i.e., 15 inches H_2O). For the majority of the tests, the start of the second day would begin with a chamber pressure 5 inches H_2O and a temperature of 90 °F, since the chamber would sit overnight without heat or circulation. Leaks would typically be at their worst when the chamber was refilled to bring the pressure back up to 15 inches H_2O at the start of Day Two. Once the target pressure was achieved, temperature appeared to have minimal or no impact on the leak. In some cases the leak actually receded or dried.

To check the mechanism causing this phenomenon, it was decided to run two tests with controlled orifice pin-holes. The two holes created were made with pins of 0.013 and 0.075 inches in diameter. When a test was initiated, the chamber pressure was first increased in increments of 5 inches H_2O while the temperature was held constant. The pressure was held at each increment for 30 minutes and the pin-hole was checked for a leak. Once a target pressure of 20 inches H_2O was reached, the process reversed. The pressure was then dropped down to 5 inches H_2O and the temperature increased incrementally until the maximum target of 140 °F was achieved. The flash heater would increase the chamber fluid temperature by 10 °F every 10 minutes. Once at 140 °F for 30 minutes, the pressure was then again increased in 5 inches H_2O increments until the maximum target of 20 inches H_2O was reached. This test format was repeated for both pin-hole samples.

Table 6.2.2 – Pin Hole Study Conditions and Results

Tank Feature	Feature Description	Test Panel Description	Cummulative Time (minutes)	Temperatures (°F)	Chamber Gauge Pressure (in H_2O)	Manometer Pressure (in H_2O)	Leak (Y/N)	Result Description
Other	Panel	0.013 Dia Thru Pinhole	30	73.2	5	5	N	Temperature constant, pressure increased
			60	72.4	10	10	Y	Droplet appears - weep
			90	71.8	15	15	Y	Weep grows
			120	71.8	20	20	Y	Weep grows
			150	71.8	5	5	N	Drained to 5 inches prior to temperature increase, droplet wiped
			170	90	6	6	N	No Leak
			180	100	6.5	6.5	N	No Leak
			187	110	7	7	N	No Leak
			198	120	6.5	6.5	N	No Leak
			212	130	6	6	N	No Leak
			230	140	5	5	N	No Leak
			255	140	10	10	N	No Leak
			270	141	15	15	N	No Leak
			300	140.8	20	20	N	No Leak
		0.075 Dia Thru Pinhole	30	70.8	5	5	Y	Seep - new droplet departure every ~25 secs
			60	69.8	10	10	Y	Seep - new droplet departure every ~15 secs
			90	69.6	15	15	Y	Seep - new droplet departure every ~5 secs
			120	69.4	20	20	Y	Seep - new droplet departure every ~4 secs
			121	66.2	5	5	N	Drained to 5 inches prior to temperature increase, droplet wiped
			145	105	5.5	5.5	N	No Leak
			175	120	5	5	Y	Leak - weep
			205	133	5	5	N	Droplet dried up
			235	140.4	4.5	4.5	N	No Leak
			265	142.4	8.5	8	N	No Leak
			295	140.6	13	13	N	Moisture in hole - no droplet
			325	140	15	15	Y	Droplet appears - weep

6.2.3.5.1 – 0.013 Inch Diameter Pin-hole

For the 0.013 pin-hole sample, the first weep droplet appeared when the pressure was raised to 10 inches H_2O and grew as it increased to 20 inches H_2O. When the pressure was dropped back down to 5 inches H_2O to start the temperature portion of the test, the original droplet was wiped off. Throughout the temperature rise sequence, no droplet formation occurred. Even once the temperature reached a maximum of 140 °F and the pressure was incrementally increased to 20 inches H_2O, no leak appeared.

Upon reviewing the sample with a cross-sectional cut and the black light, dye penetration was evident going into the scrim approximately 1 inch in both the warp and fill directions (Figures 6.2.123 and 6.2.124).

Figure 6.2.122 – 0.013 inch diameter pin hole
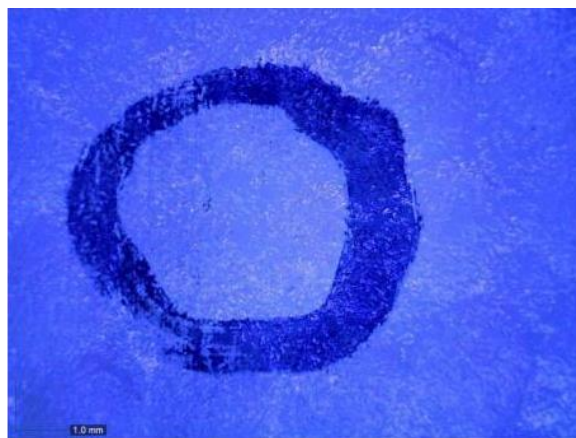
Figure 6.2.123 – Cross-sectional cut of 0.013 pin hole – dye penetration reduces the further from the hole

Figure 6.2.124 – Cross-sectional corner showing substantial dye penetration in both the warp and fill directions
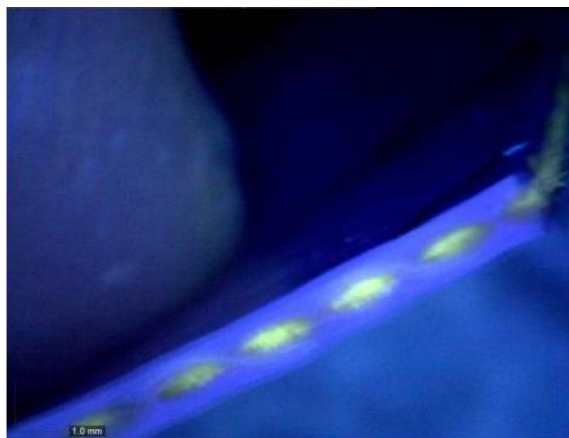
6.2.3.5.2 – 0.075 Inch Diameter Pin-hole

For the 0.075 pin-hole sample, a seep appeared immediately at the initial pressure of 5 inches H_2O and increased in rate of new droplet departure as the pressure increased (from one droplet every 25 seconds to one droplet every 4 seconds). When the pressure was dropped back down to 5 inches H_2O to start the

temperature portion of the test, the original droplet was wiped off. During the temperature rise sequence a weep droplet formed at 120 °F at 5 inches H_2O, but then proceeded to dry up as the temperature increased. Once at the maximum temperature of 140 °F, it was not until the pressure reached 15 inches H_2O that a weep droplet reappeared.

Figure 6.2.125 – 0.075 inch diameter pinhole
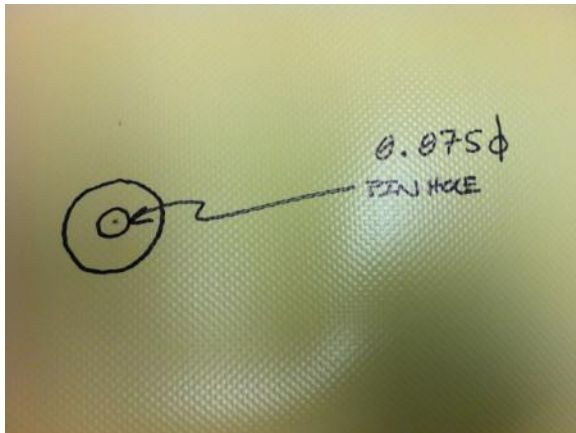
Figure 6.2.126 – 0.075 inch diameter pinhole with pin
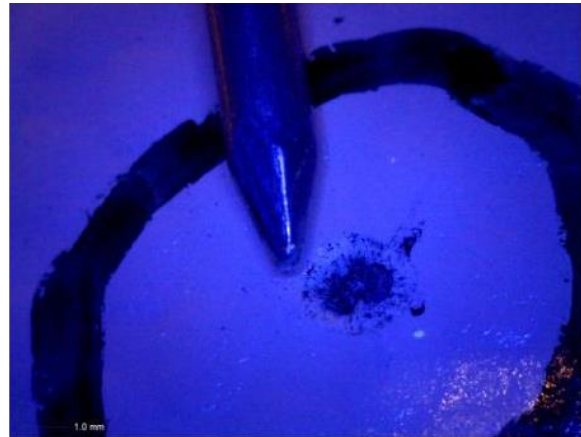
Figure 6.2.127 – Five pictures of seep droplet departure sequence showing formation of second droplet after first departs
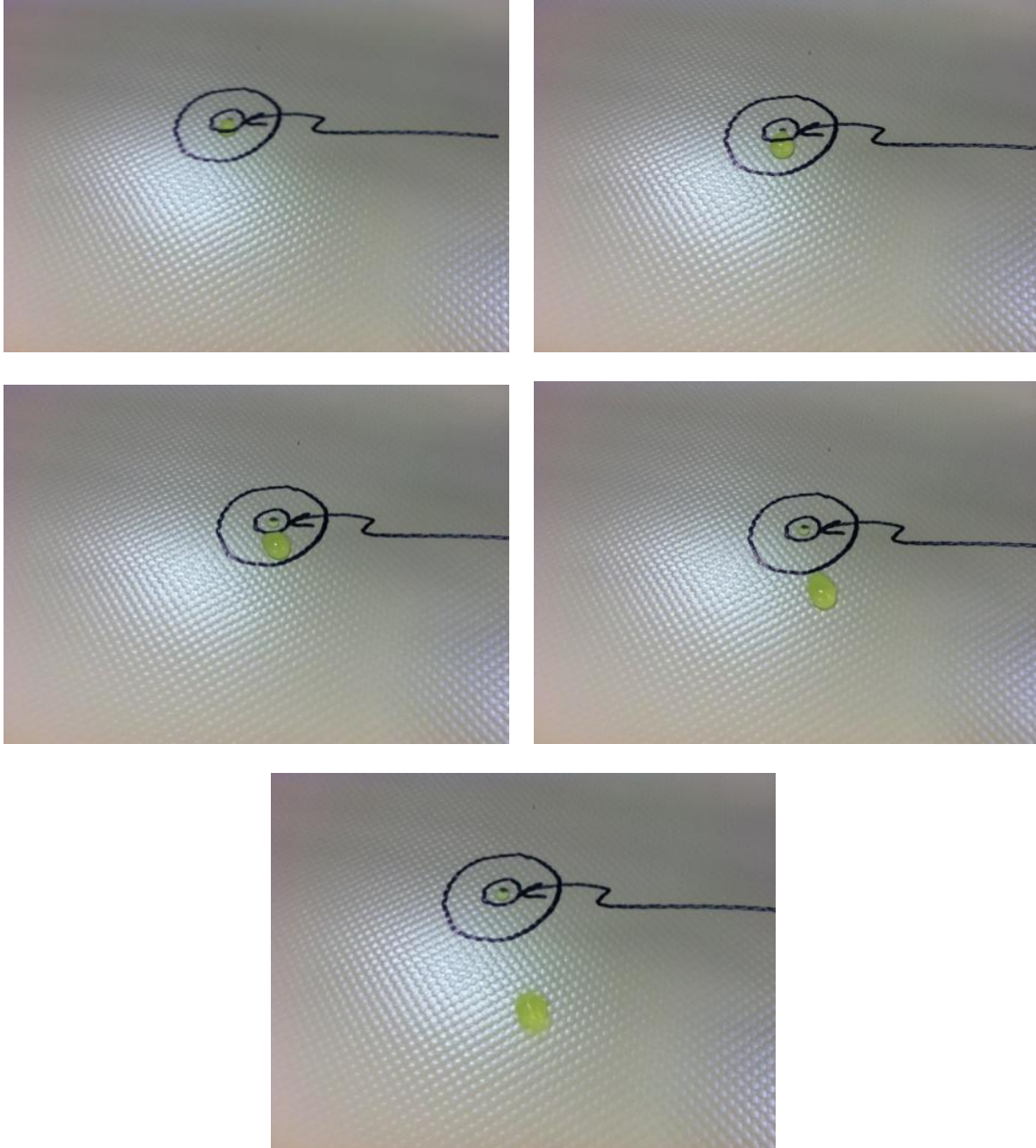
Inspections with the black light revealed no evidence of dye penetration.

In conclusion, pressure was determined as having the greatest impact on leaking. Temperature appeared to have little or no impact other than to dry up the droplets that formed. The material may stay more pliant and flexible with heat. Only after the material cools down and constricts does pressure seem to have nearly the same leak impact.

6.2.4   Leak Test Rig (LTR) Conclusions

The Leak Test Rig (LTR) successfully provided a controlled environment for evaluating a variety of different factors that contribute to leaks in collapsible fuel tanks (CFT). Welded seams, panel orientation, panel damage, fittings and seam tape were all evaluated and insight into leak mechanics was verified. To accommodate the samples into the test rig and ensure a leak-free frame, it was necessary to weld the samples into a square outer frame with a radio frequency (RF) unit. The RF welder was chosen since it lends itself well on shorter, multiple (3-5) ply thickness sections. However, it was not possible to evaluate tank corners and some closing seams since they lead to creases and folds in the material frame, thus prohibiting proper frame sealing within the LTR.

The seam testing included the centered shingle overlap (SO), alternate overlap (AO), single butt seam (SBS) and the double butt seam (DBS). Fluid transfer can occur within a coated fabric due to panel orientation or an open or exposed scrim. The shingled overlap (SO) design creates an inherent interior to exterior potential leak path while the alternate overlap (AO) design effectively "decouples" this pathway. The shingle overlap design is impacted more by differential pressure that occurs between the fluid (when filled) in the tank and the exterior ambient pressure. With the alternate overlap design, the inner alternating panels will always be at equilibrium with the fluid pressure within the tank. In addition, the external panels will always be at equilibrium with the ambient external pressure (assuming an integral panel with no other flaws). Therefore, the alternate overlap design limits the internal/external tank pressure differential impact.

Exposed or open scrim served as a means by which dyed fluid was transferred through the material. This was shown extensively in the single overlap design as well as anywhere the edge of the panel was not adequately sealed. Resultant leaks that occurred out of the exterior seam edge were visually traced back with the use of the black light through the material to the open scrim at the inlet edge.

In general, pressure differential had a much greater impact on leak propagation than did temperature, serving as the main motive force for fluid transmission through the fabric. This was initially seen in a number of tests, but especially in the Abrade 2 (Section 6.2.3.2.2). It was then verified in the 0.013 and 0.075 Dia Pinhole tests (Section 6.2.3.5) by holding pressure or temperature constant while the other was varied. Adding heat had significantly less of an impact and, in some cases, actually dried out some of the droplets and may have caused occlusion of the leak pathway. Some of this may be due to the difference in fluids (i.e., dyed water versus JP-8). In the field testing at SwRI (Section 5.4), it was noted that leak number and rate were tied to pressure as well as to temperature.

T-Seam locations whether inherent in the test panel or created when welding the test panel into the frame, were problematic. Larger droplets to major seeping were present anywhere a gap at T-Seam occurred due to a lack of adequate compound flow during RF welding. This is reflective as a major weak point in tank field experience.

The single versus double butt seam (SBS / DBS) tests provided additional insight into the advantages of having a second butt strap. Structurally, the double butt strap design provides superior seam strength, whether at a warp or closing seam. With the single butt seam (SBS), dye penetration occurred into both panels that were adjoined by the strap. With the single strap on the outside, the scrims of both adjoining panels are exposed to the tank contents. This was reflected with the dye penetration cross-sections seen for this case (Section 6.2.3.1.3). By comparison, the double butt seam (DBS) adjoining panels lacked the dye penetration. If the double butt seam is to specification, theoretically it should prevent leakage by not allowing fluid into or out of the tank panels through the seam route.

During fabrication and in-field use, storage and shipping, it is possible for a variety of events to occur which may create CFT leaks. The potential causes evaluated included scuffing or abrasion, hot air gun, chemical attack, pin holes and damage due to folding/compressing. Scuffing or abrasion needed to be paired with fiber damage or disruption for visible leakage to occur. This was evident in the difference between the Abrade 1 and 2 runs (Sections 6.2.3.2.1 and 6.2.3.2.2). The pinhole testing also reflected this phenomenon. A pinhole on one side was not adequate to create fluid transfer to another pinhole offset a distance on the opposite side through the same fiber bundle.

It did not take long for a hot-air gun to create major damage through physical incidental tip contact as well hot air flow impingement and associated compound bubbling. A hand-held hot-air gun may be used as a secondary welding operation on some tanks; especially in hard to reach areas and tank interiors. Any operation that can be performed on the internal sections or face of the tank blanket prior to tank closure should be performed.

Care should be taken in using only recommended chemicals / solvents for surface cleaning or preparation for welding. Common cleaning solvents like methyl ethyl ketone (MEK) and tetrahydrofuran (THF) may be readily available but are not recommended for this material. As shown in the LTR testing, compound attack and surface cracking can occur and lead to leaks in panels and seams.

Fitting testing helped to establish a better understanding of both the current standard design as well as the O-ring compression design alternative. The current standard design did not leak as long as the bolts holding the fitting were at a minimum torque specification of 5 ft-lbs (roughly half of the recommended 10 ft-lbs). Loose fitting bolts, which proved problematic in the field, could lead to leakage through both the bolt holes and between the fabric and the outer ring or gasket. By providing a barrier between the material scrim and the fluid, the O-ring compression design went a step further in preventing leakage. This was clearly evident in the black light analysis of the cross-sectional views between the manway tests (Section 6.2.3.3.3).

The testing of the three seam tapes resulted in similar findings. Anywhere the tape was fully adhered was successful at preventing dyed fluid flow through the scrim and no leaking occurred. In areas where a tape lift was created, a minimal clear affluent discharge appeared. This was paired with a lack of dye penetration in the adjoining cross-sectional material area. Since a rounded probe was used to produce the tape lift, the conclusion is that either partial or a minimal number of fiber bundles were exposed, thereby greatly reducing the flow through and associated dye penetration.

In summary, the leak test rig (LTR) provided a reasonable, controlled environment for the leak performance testing of most collapsible fuel tank samples. With a little future redesign, it is believed that the LTR could accommodate tank corners and other folded material or material multiple- ply samples. Chamber fluid pressure proved to be the primary motivating force behind leak formation, rate and propagation. Temperature appeared to be secondary to pressure, at least with the water / fluorescein dye solution tested. Alternate panel (AO) orientation and double butt seams (DBS) were confirmed as preferred to the shingle panel (SO) and single butt seam (SBS), respectively. T-Seams and multiple ply welded seams were consistently more prone to leakage. The material proved to be resistant to some level of damage, with surface compound pinhole and surface scuffing and folding not sufficient enough to create leaks. The need for sealing a material seam edge with tape was verified. This is especially true for any panel that has an internal edge within the tank and an opposite end on the tank's exterior (AO). Fittings proved to be sufficient as long as manway bolts retained their appropriate torque specification. If bolts loosen through use, a back-up mechanism, such as the compression O-ring, will help minimize leakage from the fittings.

7.0   Testing Program Summary and Recommendations

7.1   Conclusions

A number of important conclusions were reached during the course of the program. They were broken
down by area of impact:

I   –   Tank Design and Fabrication
II   –   Tank Qualification Testing
III   –   Tank Field Performance
IV   –   Leak Analysis and Laboratory Performance

I   –   Tank Design and Fabrication

Regarding tank design and fabrication, the following have an impact on reducing the probability of leak
occurrence and improving tank performance:

- An extensive FTA and a FMEA were performed to categorize the potential root causes for leaks
  in collapsible fuel tanks encountered in field experience and through the Technical Roundtable
  discussion.
- Designs which minimize welded seams, especially T-welds, closing seams and corners
- Relative to welding, double-butt welds provided the most consistent performance across all
  testing.
- Any corner or other tank feature which requires the welding of more than 2-ply of material to seal
  proved problematic.
- Tank designs where panel edges do not run from inside the tank to the outside (e.g., alternate
  overlap – AO) reduce the potential for leaking.
- Standard commercially available tank fittings must have provisions in place to address exposed
  scrim. The O-ring compression alternative design adequately addressed this issue without the
  need for additional sealing compounds.

II   –   Tank Qualification Testing

When integrity testing a fabricated tank, a few points were noted:

- An active air pressure test, with a continuous supply of air at a fixed pressure, appeared to be
  more effective for leak detection than one where the supply is shut off once the appropriate
  pressure level is reached.
- Through post field test tank forensics, it was evident that a number of fabrication related issues
  occurred when work was done inside of a completed tank; whether patching a "miss" with a heat
  gun or sealing exposed scrim internally.

III   –   Tank Field Performance and Leak Analysis

Important discoveries and points verified during the field test included:

- For all tanks, the peak stretch attained was equivalent to or greater than those encountered in
  larger tanks (50,000 gallons) exceeding the 7.7% fill and 1.7% warp threshold values.

- With the "stick and string" method, there is no correction for field versus factory temperature and no compensation for field based tank material stretch.
- Once a tank reaches a stretch equilibrium (i.e., three to six months field operation based on testing) filling to a tank height prescribed by a factory strapping chart may lead to over-filling the tank. In turn, this may lead to filling repeatedly to volumes in excess of the recommended 10% over-fill limit.
- Tank designs where the tank footprint does not maintain contact with the ground (Tanks 12S – 23 and Tank 29) typically had higher tank material stretch values.
- Prototype designs which kept the base grounded through design and 5-15% additional material exhibited lower stretch values at maximum allowable over-fill.
- Tank stretch measurements were very repeatable with regard to peak warp and fill stretch locations across the tanks. The "D" panel location, near the top center vent of the tank, typically had the highest stretch.
- The lowest typical stretch was measured consistently at "F", located in a tank corner. This is contrary to some historical analysis which suggests this is an area of high stretch and stress.
- The current use of strapping charts may have some impact on tank leaks by not allowing for field temperature correction, overfilling based on field tank stretch, tank settling and soil compaction. For the tanks in the study, after a year of service it was found on average that at a tank could be over filled by 10.79% or 324 gallons based on the original 3,000-gallon fill height from the fabricator strapping chart.
- Temperatures throughout the study reached the desired extremes (> 100 °F summer, < 30 °F winter). Ambient temperature was correlated directly to tank external skin temperature with a typically high R^2 value (> R^2 = 0.8).
- It was noted during testing that temperature did seem to have some impact on leak propagation, severity and rate. However, this appeared to be secondary to initial over-fill and associated pressure.

Relative to leaks logged, the following was learned:

- Although the material was tested well in excess of its recommended specification limits, there were <u>no cases</u> of seam separation, blistering or catastrophic failure
- It was definitely a worst case test, with tanks being over-filled biweekly to 130 -150% of their recommended fill volume. In some instances, the target stretch at those over-fill levels was exceeded by as much as 40%.
- The number of leaks is reasonable considering the extreme field test temperatures and material over-stretch and the fact that 16 of the 20 tank designs were completely new to the fabricators.
- The use of RF welding on multiple-ply seams (closing and corner) driven by unique tank designs, problematic FY2008 corner clamps, prototype seam tape adherence (curved surfaces), novel tank design and geometry considerations all impacted the number of leaks.
- There were a total of 282 leaks logged across 21 tanks tested through a period of 18 months.
- A large number of leaks seen in the field (>54%) were traced directly back to flaws introduced through tank fabrication.
- Out of this total, 95.7% leaks were Class I, 3.9% leaks were Class II and 0.4% leaks were Class III (only 1 occurred – external puncture).
- Fabrication introduced flaws, such as over-welding, hot air gun nicks, aggressive cleaning agents, and adhesives that may introduce leak sources. In addition, once deployed, tank field handling and conditions can introduce leaks on an event basis (abrasions, punctures).

- The two fabricators enlisted have established a solid record for producing CFTs. It clearly illustrates how subtle changes in tank design and fabrication methods enlisted can have a large impact on overall tank fabrication and performance.

IV   –   Laboratory Testing

Two types of laboratory test were run to provide further insight, the LTR and the DLC.

- Actual tank samples for LTR and DLC tests were selected based on being representative of all seam types, locations, panel orientations, and seam tapes utilized in the field study.
- The LTR provided a robust, repeatable test platform for evaluating tank features on a reduced, controlled scale.
- Chamber fluid pressure proved to be the primary driving force behind leak formation, rate and propagation. The temperature is secondary relative to the LTR testing.
- Seam shear tests and dead load testing were used to establish a baseline for tank panel and closing seam performance. The seam shear testing was conducted on all the seams to verify their integrity prior to dead load testing.
- The DLC testing highlighted weaknesses, especially in tank areas where multiple plies (> 2) of material were welded together (e.g., closing seams).
- Twenty percent of the dead load samples (16/81) did not meet the 29-day, three-year service requirement. These failures were attributed primarily to "cold weld" (IUS) and some limited weld skew issues.
- By definition, the dead load test is meant for parallel axis welds and is not the best method to evaluate welds that inherently have skew in their design. Even though there were no tanks which failed do to seams opening up in the field, a need for evaluating closing and off axis orientation welds when fabricating tanks is evident.

7.2   Recommendations for Future Work

Any tank lot strapping chart should include a correction factor that covers the applicable field operation based on tank stretch and temperature range. This correction factor will be specific for each type of material and will serve to adjust tank height to the appropriate level based on temperature. A laboratory-controlled test could be developed to help predict this correction factor. A correlation would need to be verified between this method and its tie to actual field performance.

Fuel accounting and logistics management continue to be major priorities for DLA. To that end, the most beneficial tank based system would:
- reduce fuel losses,
- provide real-time fuel accounting,
- create an automated chain of custody, and
- help capture continuous tank performance from fabrication through decommissioning.

The tank material stretch model (Figure 4.2.8) could be further investigated against empirical field data to prove its merit. Additional material testing under load and temperature may be required to verify this.

Lastly, the relationship between tank material stress and fuel diffusion rate at elevated temperatures may be worth investigating. The current cup-based diffusion rate test standard allows for testing across a range of temperatures. However, it does not account for fuel under pressure and temperature. Both fluid

pressure and temperature will contribute to material stretch and need to be considered relative to impact on diffusion rate.